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# Satellite Altimetric Measurements of the Ocean

Report of the TOPEX Science Working Group



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16. Abstract The Ocean Topography Experiment (TOPEX) Science Working Group was established in February 1980 by the Environmental Observation Division of the U.S. National Aeronautics and Space Administration.  The group was asked to consider the scientific usefulness of satellite measurements of ocean topography, especially for the study of ocean circulation. In particular the group was asked:  <ol style="list-style-type: none"> <li>1) What are the scientific problems that can be studied using altimetric measurements of ocean topography?</li> <li>2) To what extent are <u>in-situ</u> measurements complementary and required?</li> <li>3) What accuracy, precision, and spatial and temporal resolutions are required of the topographic measurements?</li> <li>4) What are the errors associated with the measurement techniques?</li> <li>5) What are the influences of these errors on the scientific problems addressed under the first question?</li> </ol> The Jet Propulsion Laboratory of the California Institute of Technology was assigned the responsibility for conducting the TOPEX definition study. This included supporting the Science Working Group, defining an operational system for			
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# **Satellite Altimetric Measurements of the Ocean**

**Report of the TOPEX Science Working Group**

March 1, 1981

National Aeronautics and  
Space Administration

**Jet Propulsion Laboratory**  
California Institute of Technology  
Pasadena, California



Frontispiece. Oceanic variability along the northern California coast on 6 September 1979 as seen by a thermal-infrared radiometer on board the NOAA-6 weather satellite (from Kelly, 1980). Such images, while tantalizing, are available only on cloudless days, and provide only qualitative impressions of the oceanic circulation. We explore in this report altimetric techniques for quantitative, continuous studies of features such as these.

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OF POOR QUALITY

## FOREWORD

The Ocean Topography Experiment (TOPEX) Science Working Group was established in February 1980 by the Environmental Observation Division of the U.S. National Aeronautics and Space Administration.

The group was asked to consider the scientific usefulness of satellite measurements of ocean topography, especially for the study of ocean circulation. In particular, the group was asked:

- 1) What are the scientific problems that can be studied using altimetric measurements of ocean topography?
- 2) To what extent are *in-situ* measurements complementary and required?
- 3) What accuracy, precision, and spatial and temporal resolutions are required of the topographic measurements?
- 4) What are the errors associated with the measurement techniques?
- 5) What are the influences of these errors on the scientific problems addressed under the first question?

The Jet Propulsion Laboratory of the California Institute of Technology was assigned the responsibility for conducting the TOPEX definition study. This included supporting the Science Working Group, defining an operational system for measuring ocean topography based upon the recommendations of the Working Group, and estimating the cost of conducting such a topographic experiment. This document presents the results of the study by the Working Group.

Robert Stewart  
Project Scientist

## **TOPOGRAPHY EXPERIMENT (TOPEX) SCIENCE WORKING GROUP**

Carl Wunsch (Chairman)	Massachusetts Institute of Technology
R. J. Anderle	Naval Surface Weapons Center
Harry Bryden	Woods Hole Oceanographic Institution
Bruce Douglas	National Ocean Survey
David Halpern	NOAA Pacific Marine Environmental Laboratory
William Haxbe	Lamont-Doherty Geological Observatory
James Marsh	NASA Goddard Space Flight Center
Richard Rapp	Ohio State University
Joseph Reid	Scripps Institution of Oceanography
Friedrich Schott	University of Miami
Robert Stewart (Project Scientist)	Jet Propulsion Laboratory, and Scripps Institution of Oceanography
Byron Tapley	University of Texas
Dana Thompson	U.S. Naval Ocean Research and Development Activity
Edward Walsh	NASA Wallops Flight Center
Klaus Wyrtki	University of Hawaii

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*NACOA believes that ... a family of oceanic satellites, ... evolved over the next decade, can provide the full range of oceanic ... measurements required for operational and scientific purposes. This technology will improve our ability to develop and utilize oceanic resources, such as fisheries, oil and gas, and deep-sea minerals, as well as provide for more efficient use of our naval and maritime fleets ... this family should include ... a capability to measure the height of the sea precisely enough for observation of ocean currents.*

*National Advisory Committee  
on  
Oceans and Atmosphere*

## SUMMARY

The large-scale movement of water in the ocean has many direct consequences for life on Earth. Of these, perhaps the most important is its amelioration of the world's climate. Without the ocean, large areas of the Earth on which we live would either be unbearably hot or unbearably cold compared to their present states, and life as we know it would be very different. Two processes are involved. First, the oceans carry roughly one-half the heat supply moving from the equator to the poles (the atmosphere carrying the remainder), thus greatly reducing the very large temperature contrasts that would otherwise occur. Second, the large heat capacity of the sea greatly reduces the seasonal fluctuations in temperature, especially at higher latitudes, leading to the equable climate of our continent.

The ocean is important in a great variety of other ways. It has been fished for food since prehistoric times, and today provides a large fraction of the world's food supply. Yet only a few very limited regions of the ocean can sustain important fisheries (the Grand Banks, the coast of Peru, and the Gulf of Alaska, for example), primarily because of the special oceanic flows required for high productivity. These special environments are often fragile, waxing and waning in ways as yet unpredictable (the Peruvian and California anchovy fisheries are prime examples); and the conditions that lead to particularly good fishing at one time and place and not at another are usually determined by oceanographic and meteorological conditions on a much broader scale.

The oceans carry the great fleets of commerce that move the bulk commodities essential to modern society. The tanker trade carrying the global petroleum supply is perhaps the most striking example. But to a great extent, coal, grain, cement, automobiles, and chemicals are all transported by sea. The economics of this commerce depends upon the comparative cheapness of ships and their ability both to avoid dangerous areas (Cape Agulhas in winter) and to take advantage of known current systems (the Gulf Stream).

In a somewhat less obvious way, many other societal concerns are bound up in the movement of ocean water (usually called the "general circulation"). Amongst several possible examples we will mention only two more. The disposition of radioactive wastes is a major concern of the day. Seabed disposal is one of several alternatives being actively considered. But the extent to which this will prove to be a realistic and safe option depends in large part upon the rate at which currents will carry potentially dangerous leakage from even the best of disposal packages toward fisheries, coastal areas, and other sensitive locations.

Of more immediate concern, many of the operational problems involved in maintaining the Navy's sea-based deterrent and its ability to defend the United States are

determined in some ways by the ocean circulation. For example, the very large under-water acoustical variations found in the vicinity of the Gulf Stream and Kuroshio (Japan Current) systems are the result of the very strong flows of those currents away from the boundaries and into the interior of the sea. These places thus provide both hiding places and hunting grounds.

The implications of the ocean circulation are clear. But over the past several years many more questions have been raised by society than oceanographers know how to answer. Many presuppose a detailed knowledge of the internal workings of the ocean, knowledge that is just not available today.

Again, a few representative examples must suffice. Recent extreme weather in the United States and elsewhere has raised questions about whether or not climate is changing. While it is known that the ocean plays a major role in determining our present climate as described above, there are really no adequate means for actually deciding the question of whether anything in the ocean is changing in ways that are significant for climate. The present climatic state of the ocean is only known in the crudest terms; whether that state is changing is unknown.

A related question concerns the problem of carbon dioxide with all its potential implications not only for national and international energy policies, but also for conceivably catastrophic climatic changes and their implications for world food supplies and security. Oceanographers know that the ocean is important in deciding whether carbon dioxide will produce serious problems in the short term and in the long term. The ocean plays at least a dual role—it absorbs some of the carbon dioxide from the atmosphere, thus reducing the rate of heating of the atmosphere. But once the atmosphere is heated, the ocean will respond to the changed temperature. The rates at which these things will occur are dependent upon knowing how the water in the ocean circulates and how it will respond to changing external forces.

A further important question recently asked of the oceanographic community was what are the consequences of an oil spill on Georges Bank fishing grounds? The answer is not simple, involving as it does both biological processes and a knowledge of the water movement and how it would change under changing meteorological conditions and changing (but unobserved) processes in the deep sea.

The preceding discussion points out a few examples of the way in which ocean circulation affects our daily lives. Climate changes, fisheries, commerce, waste disposal, and defense are all involved. In examining these examples it is clear that the ability to measure ocean circulation is both a necessary and critical element in understanding the influence of environment on society, and that this ability is not available today.

### **Towards Observing the Ocean**

The TOPEX Science Working Group, in response to a NASA request, has reviewed the problem of observing the circulation of the ocean and understanding its behavior. In responding to this request the group has reviewed existing knowledge of the circulation, the tools that now exist for observing it, and the possibilities opened up for the future by the development of satellites capable of precise altimetric measurements from space, satellites such as Geos-3 and Seasat, as well as other non-space technologies which could contribute to a unified observing system.

A major conclusion of the study is that the most serious obstacle to understanding the ocean circulation is the absence of any widespread means for observing it. At present, oceanographers rely on ships, buoys, drifting floats, and moored instruments, sources of information that are well suited to short term (a few months) regional studies (areas a few hundred kilometers across). But no existing method permits observation on the global scale that is required to measure and understand the ocean as an entity. (The Science Working Group has drawn an analogy with the atmosphere. An

Table 1 Oceanographic Phenomena

Phenomenon	Typical Surface Expression	Period of Variability	Comments
Western boundary currents (Gulf Stream, Kuroshio)	130 cm/100 km	days to years	Variability in position, and 25% variability in transport
Large gyres	50 cm/3000 km	one to many years	25% variability expected
Eastern boundary currents	30 cm/100 km	days to years	100% variability expected, maybe reversals of direction
Mesoscale eddies	25 cm/100 km	100 days	100% variability
Rings	100 cm/100 km	weeks to years	100% variability, growth and decay
Equatorial currents	30 cm/5000 km	months to years	100% variability

existing international system—the World Weather Watch— reports twice daily the state of the atmosphere. This global system provides data for weather predictions, and through the accumulation of data over time, also provides the basis for understanding past and present climates and perhaps for predicting future climate as well. We know that the ocean also contains both a "weather" and a "climate." But there is no equivalent of the World Weather Watch; no international, routinely reported observations except at isolated points and isolated times. For this reason knowledge of the sea has lagged far behind that of the atmosphere.)

The Science Working Group has concluded that a system capable of routinely observing the world's oceans should be a high priority goal. Experience with the present *in situ* technologies, and with past satellite missions leads to the conclusion that satellite altimetry is the only method with a demonstrated capacity to address the specific requirements for observing ocean circulation mandated by pressing national problems. The rationale for this conclusion is discussed in this report, and may be summarized as follows: (a) The large-scale movement of water in the sea tends to manifest itself as an elevation change of the sea surface proportional to the strength of the surface currents. If the currents are time varying, then too is the surface elevation. (b) This variation of sea surface elevation can be measured by altimetry, and provides a quantity, the surface pressure of the sea (*not* of the atmosphere) directly related to water movement below the surface through the known equations of motion. (c) Altimetry works in any weather and only heavy rain may cause difficulty in interpreting the data. And (d) the requisite accuracies have been demonstrated through prior missions (Geos-3, Seasat) conducted by the National Aeronautics and Space Administration.

Rough estimates of the typical values of these changes in elevation produced by a few of the many large-scale phenomena in the sea are summarized in table 1. The prime goal of an altimetric mission is to measure the surface signature of these phenomena with sufficient accuracy, precision, and frequency in time and space. Specific means for doing this are discussed in the main body of the report.

The Science Working Group recognizes that an altimetric mission having perfect accuracy and precision, while providing a large number of benefits, is not in itself

capable of completely determining the oceanic circulation. Rather it provides a context in which other instruments, both existing and under development will become much more powerful. Together with altimetry they will go a long ways toward producing a system for observing the sea. For the first time, oceanographers would be provided with the equivalent of the surface barometric pressure charts that meteorologists have used with such great effectiveness for many years.

### **Proposed Mission**

Altimeter systems are basically very simple: they use a precision radar to measure the distance from the spacecraft to the sea surface. If the height of the spacecraft relative to a reference surface (the geoid) is also known, then it is possible to calculate the changes in height of the sea surface produced by currents, and to observe the changes through time. In practice, it is necessary to correct for many errors if the measurement is to be made to useful accuracy. Based upon experience with Geos-3 and Seasat, and accounting for existing advances in technology and science, the Science Working Group together with a precision orbit determination team have summarized the error budget of a realistic altimetric mission (table 2). Measurements with these accuracies, while difficult, seem achievable subject to some caveats described below. Should an actual mission fail to achieve these goals to within about a factor of three, the mission would still fulfill its primary goals.

An examination of the various sources of error leads to the conclusion that a satellite altimetric system could now be flown using state-of-the-art techniques. The Science Working Group thus recommends that NASA conduct an experiment, called the Ocean Topography Experiment (TOPEX), having the following major components:

*Satellite*—The experiment requires a satellite with instruments capable of measuring the height of the satellite above the mean sea surface with an accuracy of two centimeters.

*Orbit*—The satellite should be in a nominal circular orbit with a height of 1300 km, an inclination of 65°, and a subsatellite track that repeats within approximately one kilometer every ten days, but with the capability of changing the pattern of the subsatellite track if necessary.

*Duration*—The experiment should last a minimum of five years in order to observe the interannual variability of ocean circulation.

*Geoid*—An accurate geoid is essential not only for the calculation of the time-variable and time-averaged ocean circulation, but also for the accurate determination of the satellite's orbit. The Science Working Group therefore recommends that the special purpose gravity-measuring mission, Gravsat, be flown for the purpose of determining Earth's gravity field and geoid. The Gravsat User Working Group has already estimated the accuracies for that mission, and they appear to be compatible with those required by TOPEX.

*Winds*—The surface currents of the ocean are driven primarily by the winds, and thus TOPEX requires timely measurements of the global oceanic wind field. The mission assumes that these measurements will be made by a scatterometer such as that proposed for the Noss spacecraft. Should this instrument not be available, the Science Working Group will consider the desirability of adding it to TOPEX.

*Data System*—Particular attention must be paid to the problem of dealing with the TOPEX data. We recommend not only that a complete data-handling system be in operation at the time of launch, but also that work be started now to develop, prior to launch, techniques for maximizing the usefulness of the data.

*Supporting Observations*—We expect that TOPEX will be a key element in the global climate programs now being discussed by the international scientific community, and that, in turn, the climate programs will be supporting a number of *in situ*

Table 2 TOPEX Error Budget

Source of Error	Cause of Error	Uncorrected Error (cm)	Corrected Error (cm)	Wavelength (km)
Altimeter	Altimeter noise		1.5	20
Altimeter	Ocean waves	4	1.0	1000
Troposphere	Mass of air	240	0.7	1000
Troposphere	Water vapor	20	1.0	50-500
Troposphere	Rain	—	—	
Ionosphere	Free electrons	10	0.5	50-10,000
Orbital error	Gravity	5 (km)	0.7	10,000
Orbital error	Drag	5	3.6	10,000
Orbital error	Solar radiation	30	7.0	10,000
Orbital error	Earth radiation	3	1.0	10,000
Orbital error	Station location	10	3.0	10,000
Orbital error	Timing		0.2	10,000
Sea level	Weight of air	50	3.0	200-1000
Sea level	Geoid	100 (m)	1.5	200

The table summarizes the errors in satellite measurements of ocean surface topography. Further details are given in section 4 and appendix B. This brief summary assumes: (a) a dense spherical satellite orbiting at a height of 1300 km, tracked by a realistic network of laser stations, (b) accurate measurements of Earth's gravity from the Gravsat mission, (c) additional data from a dual-frequency radiometer and dual-frequency altimeter on the spacecraft, (d) surface pressure with an accuracy of 3 millibars from global weather charts, (e) a spacecraft clock having an accuracy of 100  $\mu$ s, (f) an average wave height on the sea surface of two meters, and a wave skewness of less than 0.1, and (g) no data collected in heavy rain. The corrected error is the error in measurements made along a single satellite pass crossing the ocean basin. We expect that long-term averages of many passes will substantially reduce the random error.

observations useful for both calibrating and interpreting the ocean-topography measurements. To enhance the mutual benefits, TOPEX should maintain close ties with those who are now developing the climate plans.

*Timing*—Because both *in situ* observations and global winds are important elements of the TOPEX mission, it is important that TOPEX have a maximum period of overlap with field programs sponsored by the World Meteorological Organization and with Noss. The improved knowledge of the geoid sought from the Gravsat mission need not precede the launch of TOPEX because that data can be used retrospectively. Nonetheless, it is highly desirable that the six-month-long Gravsat mission be flown sometime before the end of the five-year TOPEX mission.

## **Applications and Benefits**

The major goal of TOPEX is to improve substantially our understanding of the ocean circulation and its fluctuations. Considered as a purely scientific endeavor, this goal is of great importance by itself, for it will provide the first comprehensive, global insight into ocean dynamics. Beyond this lie a wide range of other important benefits. In part, these benefits stem directly from an improved understanding of the ocean circulation; in part they are a by-product of data collected for the experiment.

Into the first category will fall many of the societal problems noted in the introduction. They include the role of ocean circulation in past and future climate, the management of prime fishing grounds, understanding the movement and fate of both stable and radioactive pollutants, the collection of very much improved surface current and wave information for more efficient operation of commercial and naval vessels, and charting areas of significant acoustic variation. All of these problems have been briefly discussed above, but there are numerous other important examples, a few of which deserve mention.

Coastal navigation and the prediction of the trajectory of spilled oil and other pollutants depend in part on an accurate knowledge of tides, tidal currents, and surface winds. For example, modern supertankers frequently cross shoal areas, such as the approaches to the English Channel, only slightly deeper than their draft, and their safety depends on accurate bathymetric charts and tidal predictions. Today, coastal tidal forecasts in many areas are based on incomplete models which rely on sparse data from shore-based facilities. Using satellite altimetry it will be possible to produce accurate tidal predictions not only for coastal regions, but also for deep water.

Many populous cities, harbors and expensive installations are in coastal areas subject to damage and flooding by hurricanes. Measurements of currents and waves made by a satellite altimeter, when combined with bathymetry and theoretical studies, will lead to improved predictions of storm surges, flooding, and erosion produced by major storms.

Offshore structures and facilities must be designed to withstand severe wave and current loading regardless of whether or not they are founded on the bottom or floating on the surface. Offshore oil rigs, drill ships, mining operations, coastal nuclear power plants, ocean-thermal-energy conversion facilities, and more all need reliable estimates of wave and current climates. Information derived from altimetric observations, when observed over a period of many years will lead to the desired climatological summaries.

The destruction of some offshore facilities potentially carries with it the significant environmental hazards; an oil spill on Georges Bank was mentioned above as an example. There are other examples of the complex links between biological processes and the physical environment. One natural example which influences Florida's economy is the phenomenon of the red tide. A growing body of evidence suggests that normal variations of the Loop Current, as it passes from the Caribbean through the Gulf of Mexico, causes an upwelling of nutrient-rich waters upon which the red tide organisms thrive. Although altimetry cannot solve the problem, it could be used to study the variability of the loop current from which prognostic models could be derived.

Other, less obvious benefits also accrue from TOPEX, but their consequences are by-and-large outside of the oceanographic sphere. For example, the accurate geoid produced as a necessary prerequisite for the determination of surface currents will be of great use to geophysicists, as noted by the National Academy of Sciences. It will also lead to significant improvements in the potential accuracy of inertial navigation systems used by ships, aircraft, and submarines; and will yield maps of the locations of bathymetric features such as seamounts, of interest to geophysics, fisheries, and the Navy.

A determination of the electron content of the ionosphere, another byproduct of the experiment, will be useful for the prediction of the propagation of short-wave radio signals used for communications, as well as for aeronomy.

Finally, we note that although TOPEX was not designed as an "operational" mission, it could provide immediate access to information of use to those who must operate on the sea, and at the same time, would be an informative forerunner for a truly operational, optimally designed, oceanic satellite.

In summary, we conclude that there are many potential uses for precise altimetric data which extend from basic oceanographic research to applied problems which affect our daily lives. These problems include those related to significantly improving our understanding of the ocean as a whole, offshore energy production, commerce, coastal zone problems, communications, and national defense. We also conclude, using the experience gained from the Geos-3 and Seasat missions, that the accuracy and precision needed to address these problems can be achieved. In an era of increasing demands for pertinent information potentially capable of providing new insight to these problems, the TOPEX Science Working Group recommends that serious consideration be given to the experiment that we have outlined in this report to the National Aeronautics and Space Administration.

## 1. Introduction

The movement of water in the ocean has an impact upon human life in a variety of ways. On the Earth, climatic contrasts between pole and equator are greatly ameliorated by the presence of the ocean because of its large heat capacity and its contribution to the movement of heat from equator to poles. Much of the weather we experience is spawned over the ocean through complex air-sea transfer processes. The important global fishing grounds are limited to small geographical areas dominated by special oceanic flows, and the movement of chemical tracers and pollutants in the sea is of present and future importance. For example, the rate at which the burning of fossil fuel causes the temperature of the air to rise is determined to a large extent by the rate at which the ocean will be able to absorb the  $\text{CO}_2$  and by the rate at which the ocean warms due to increased atmospheric heating (National Research Council, 1979a).

Many things about the ocean are poorly understood, largely because the ocean is so difficult to observe. It is a global fluid, and like the atmosphere it appears to have both a climate and a weather. But unlike meteorologists, oceanographers have no global observation system, only fragmentary and ephemeral regional observation systems. There are several reasons for this paucity of observations, but the primary one is that the ocean is extremely difficult to measure. It is opaque to electromagnetic radiation, so it cannot be sounded with conventional instrumentation. Instruments left in the water must operate in a corrosive, high pressure environment. If they are placed in proximity to the sea surface, they are subject to enormous, repetitive, dynamic stresses, and to biological fouling. Conventional platforms (ships) are of necessity very slow (15 knots maximum speed) and very expensive to operate. Furthermore, in contrast to weather prediction, there has been no perceived requirement to forecast the ocean conditions. Thus, national governments have not felt obliged to establish large-scale measurement networks for routine reporting of the state of the ocean.

The past decade has shown oceanographers that to understand fully the workings of the global ocean, and thus to understand fully its impact on both the problems stated above and others (fisheries, climate, weather, and defence) we require an observation system analogous to that available to meteorologists. Given the global nature of the problem, only satellite systems have the potential for addressing the need. But there are special difficulties. Satellites are capable of sounding the atmosphere from top-to-bottom because the atmosphere is semitransparent to electromagnetic radiation. But because such radiation does not penetrate the ocean, measurements from space are fundamentally restricted to observations of the sea surface. This makes the interpretation of the results more challenging.

Satellite measurements of the sea surface have been of two types—active and passive. The passive measurements are commonly used to measure the color, temperature, and ice cover of the ocean. Active measurements have been used to infer sea-



surface roughness, which provides estimates of wave height and structure and sea-surface elevation. The latter measurements are made by illuminating the sea surface with a burst of electromagnetic radiation and measuring intensity, time and structure of the return.

Two satellites, Geos-3 and Seasat (Mather, Coleman, and Hirsch, 1980; Cheney and Marsh, 1981) have demonstrated that meaningful and useful measurements of sea-surface elevation can be made. The purpose of the present study is to explore the feasibility of further measurements of this type and their potential impact upon programs for measuring and understanding the ocean. The measurement of elevation (essentially altimetric) has been singled out for this study for a number of reasons, but four are particularly noteworthy. First of all, surface elevation is known to be a comparatively simple function of processes occurring at depth in the ocean, in contrast to sea-surface temperature and other variables. This important conclusion is a consistent result of both theory and observation. Secondly, unlike many other satellite measurements, altimetry is not limited to cloud-free periods. Thirdly, surface elevation is linked directly, through the equations of motion, to the large-scale water movements which are of concern in many societal problems. And finally, the Seasat and Geos-3 results have demonstrated that the requisite accuracies are likely to be attained, and thus these data permit us to make plausible estimates of the impact of additional measurements.

Any satellite program produces more information than that for which it was designed. So it is with satellite altimeters. They measure with varying accuracies wind speeds, wave height, changes in sea level along coasts, rainfall, ice boundaries, the level of plains on land, the contours of height of continental glaciers, and other phenomena of interest to Earth scientists. In addition, auxiliary measurements useful for reducing errors in satellite altimetry produce useful information on water vapor in the troposphere and free electrons in the ionosphere. A discussion of these measurements, if included in our study, would lead us from our main theme of the general circulation of the ocean. They are thus treated only briefly at the end.

## 2. The Oceanic Circulation

A determination of the general circulation of the oceans has been a goal of scientists from the very beginning of oceanography. The general circulation is, loosely speaking, the large-scale, time-averaged movement of water. The ocean is a global fluid with large variability both regionally and temporally, and it contains different dynamical and kinematical regimes, much as the atmosphere does. The circulation of the ocean is driven directly and indirectly by the wind field, and by atmospheric heating at the equator and cooling near the poles. The spatial scales involved in the resulting circulation run from order 30 km up to the size of the largest ocean basins (of order 10,000 km). A fundamental feature of the ocean is that it is vertically stratified, and thus the flow of water is a function of depth as well as geographical position. Superimposed on the time-averaged flows are a variety of time-dependent processes, and these render the determination of the average extremely difficult. These time-dependent processes also contribute dynamically to the large-scale mean distribution of properties. From the past decade of work, it is known that over great areas of the ocean, this variability (often called mesoscale variability or "eddies") can have energy levels one or more orders of magnitude greater than that of the mean flow (figure 2.1).

Through eddy Reynolds stresses, the field of variability is capable of generating time-averaged movement of the various fields. These fields include passive tracers such as tritium, dynamically active tracers such as heat and salt, and dynamical quantities like momentum and energy. Because these different properties of the water can be transmitted and mixed differently, the general circulation of the ocean cannot be defined uniquely. The definition of the circulation depends on the property that is studied.

Superimposed on these large-scale circulations are a host of smaller-scale higher-frequency phenomena such as internal waves. These are not part of the circulation *per se*, but they can contribute to the circulation indirectly by controlling the processes of small-scale mixing in the ocean which ultimately affect the distributions of large-scale properties.

### 2.1 The Geostrophic Relationship

Generally speaking, water movements having spatial scales greater than about 30 km and time scales longer than about a day are in geostrophic balance to a very good first approximation. This means that, to lowest order, the velocity field is such that the Coriolis force is balanced by the pressure field. Thus water movement tends to be along, rather than down, the pressure contours, just as winds in the atmosphere circulate around highs and lows. The pressure field in the ocean manifests itself as a slope of the constant-density surfaces (isopycnals) in the sea relative to level (geopotential) surfaces. The sea surface itself is a special case of an isopycnal surface.

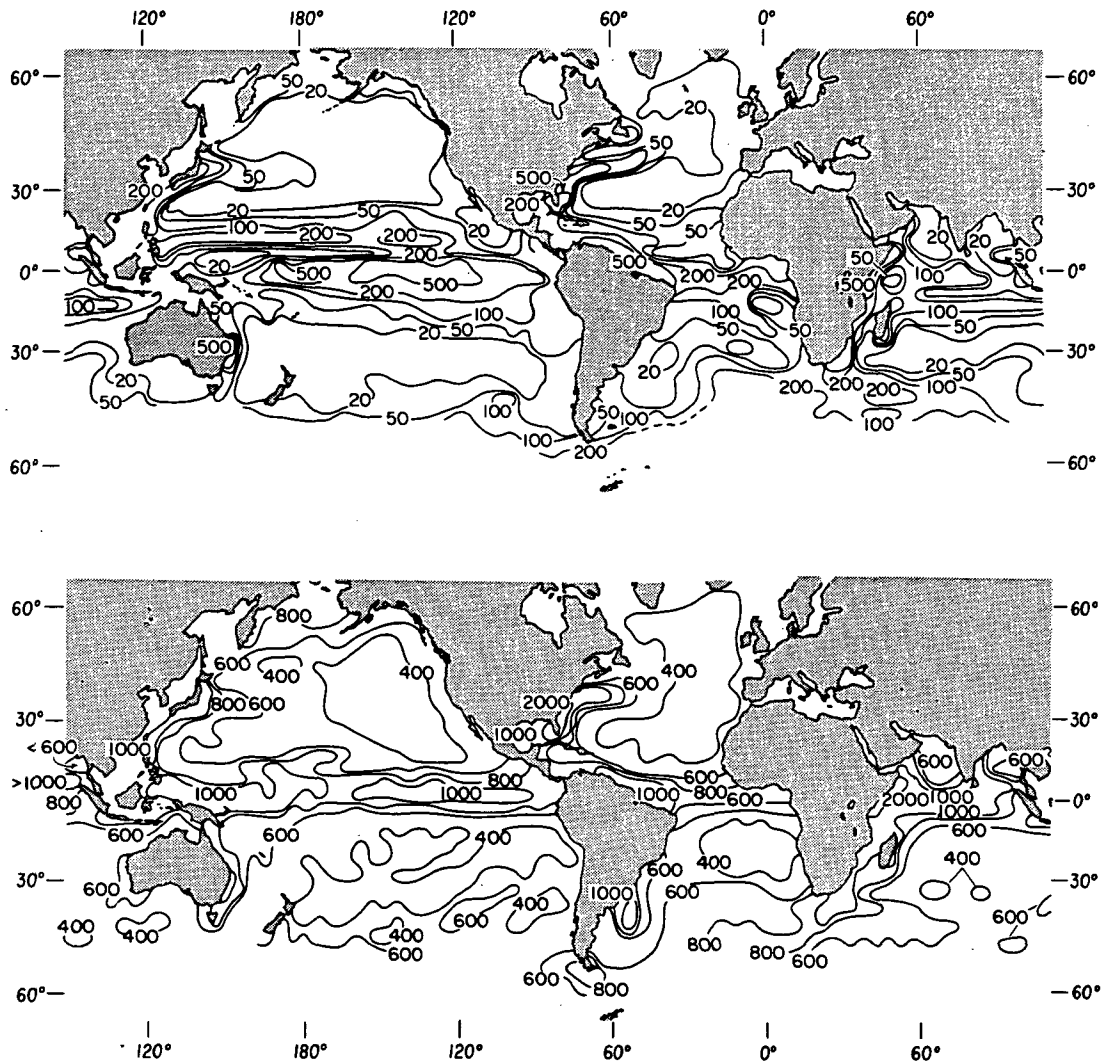


Figure 2.1 Upper: kinetic energy per unit mass of the mean surface flow based on  $5^\circ$  square averages. Lower: eddy kinetic energy of the surface per unit mass based on  $5^\circ$  square averages. Note that the variable flow tends to have considerably greater energy than the mean (from Wyrki, Magaard, and Hager, 1976).

Most large-scale motion in the sea is what oceanographers term "quasi-geostrophic," meaning simply that the motion is not perfectly geostrophic. Perfect geostrophic balance does not permit any time evolution of the field and does not allow any forces to act, implying that there are no sources or sinks of energy and momentum. But both in theory and practice, the deviations from geostrophy required to produce the necessary fluxes of energy and momentum are very small, and not normally observable by *direct* measurement.

Given the assumption of geostrophic balance, oceanographers proceed to determine ocean currents as follows.

The statements that the ocean is nearly in both geostrophic balance and hydrostatic equilibrium are expressed mathematically (in local Cartesian coordinates) by

$$-fv = -\frac{1}{\rho} \frac{\partial p}{\partial x} \quad (1)$$

$$fu = -\frac{1}{\rho} \frac{\partial p}{\partial y} \quad (2)$$

$$0 = -\frac{\partial p}{\partial z} - g\rho \quad (3)$$

where  $f = 2\Omega \sin(\theta)$  is the Coriolis parameter,  $\theta$  is latitude,  $\Omega$  is the rotation rate of the Earth (one rotation per day),  $g$  is the local gravity,  $p$  is pressure,  $\rho$  is density,  $z$  is the vertical coordinate,  $v$  is the component of velocity normal to the  $x, z$  plane, and  $u$  is the component normal to the  $y, z$  plane. Let us focus on  $v$ . We can combine equations (1-3) to give

$$v(x, z) = \frac{g}{f} \int_{z_0}^z \frac{\partial \rho}{\partial x} dz + v_0(x) \quad (4)$$

where  $v_0$  is an unknown constant of integration dependent upon the arbitrary level  $z_0$  (reference level) from which the integral is begun. By using temperature and salinity measurements from ships and an equation of state, oceanographers can compute the first term of (4), often called the "relative velocity" or "thermal wind." The constant of integration (reference velocity) is normally unknown. A measure of  $v$  at any depth  $z$  for a given  $x$  fixes  $v_0$ . For example, if the surface velocity  $v_s(x)$  were known, the reference level  $z_0$  could be chosen to be the surface  $z_0 = 0$  and we would thus have

$$v(x, z) = \frac{g}{f} \int_0^z \frac{\partial \rho}{\partial x} dz + v_s(x) \quad (5)$$

But the surface velocity may be written as

$$v_s(x) = \frac{g}{f} \frac{\partial \zeta}{\partial x} \quad (6)$$

where  $\zeta$  is the elevation of the ocean surface relative to a level surface, *i.e.* the geoid. Thus, a measurement of the slope of the sea surface can determine the surface geostrophic velocity in the ocean if the relative velocity is also known. But note that the surface geostrophic velocity is *not* the total surface velocity. Other contributions are discussed below.

In the past, the sea surface elevation  $\zeta$  was usually computed under the *ad hoc* assumption that the 1000 decibar pressure level coincides with an equipotential gravity surface; and figure 2.2, taken from Wyrki (1975, 1979), is typical of the kind of picture built up over the past 100 years by shipborne oceanography.

Under the special assumption that  $D$ ,  $\theta$ , and  $\rho$  are nearly constant, the total volume transport of water  $V$  in an ocean of depth  $D$  and width  $L$  is immediately known from  $v_s$  in (5), and it may be written

$$V = \int_0^L \int_0^D v_s(x) dz dx = \frac{gD}{f} [\zeta(L) - \zeta(0)] \quad (7)$$

This depends upon  $\zeta$  only at the end points. That is, the corresponding transport of water is independent of the width of the ocean for a given "head."

Simple theoretical considerations (*e.g.*, Blumen, 1972; Pedlosky, 1979) suggest that the shortest distance over which geostrophic flows of any significance occur is about 30 km (the baroclinic Rossby radius of deformation). The largest scales of interest are ocean-basin wide, which in the Pacific are about 10,000 km.

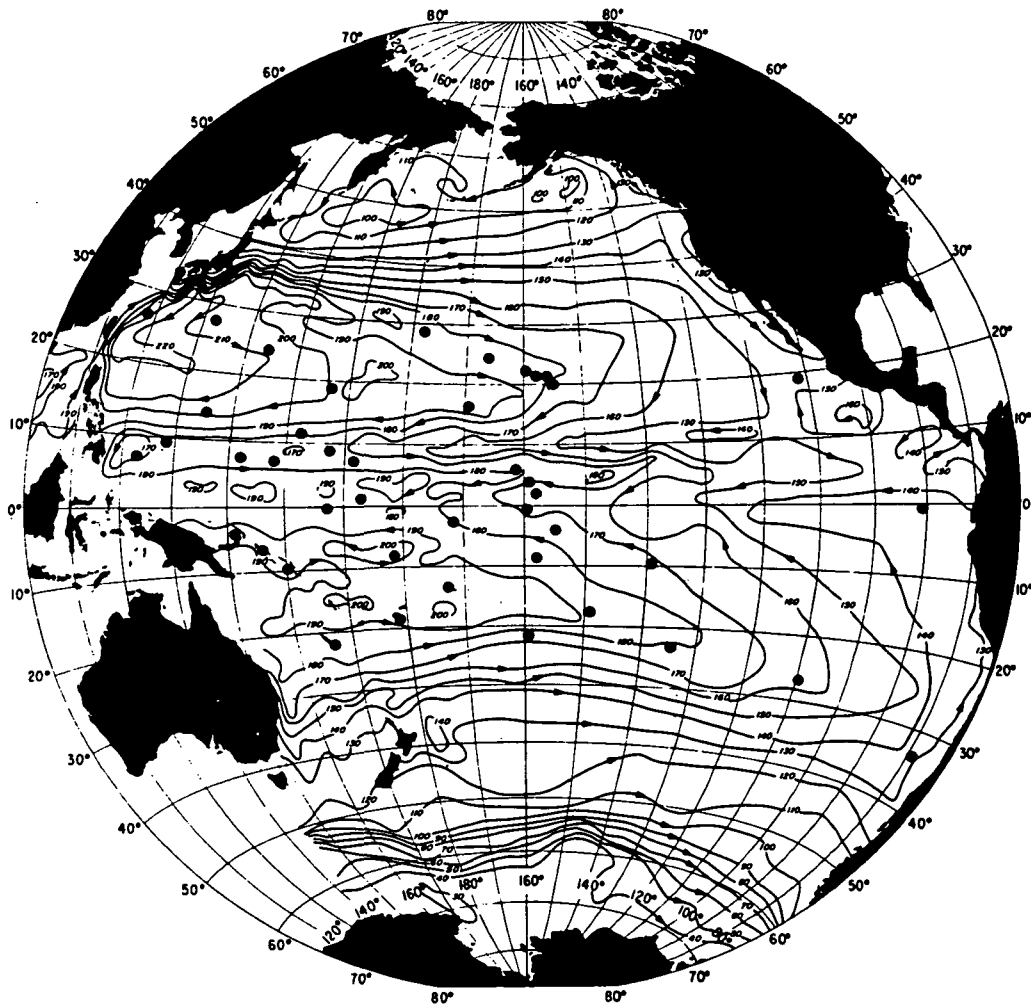


Figure 2.2 Sea-surface elevation relative to the geoid, computed under the assumption that the 1000 decibar pressure level coincides with a gravitational equipotential surface. The large dots denote the position of existing tide gauges in the Pacific network (from Wyrski, 1979).

Because the ocean is a complex turbulent fluid, the different geostrophic scales are linked together both kinematically and dynamically. For example, the very intense flows associated with western boundary currents (the Gulf Stream and Kuroshio) have a cross-stream scale of order 100 km; but the return flows, which are required to conserve mass, seem to occur from this 100 km scale on up to the ocean basin-wide scale. Thus, a determination of the 100 km scales of flow can strongly constrain and determine the large scales—and vice versa. This scale relationship is kinematic.

There are dynamical links as well. In fact, a useful definition of a turbulent fluid is that there should exist strong flow of energy from one spatial and temporal scale to others. More specifically, we anticipate that the scales on order several-hundred kilometers, the mesoscale (including both the part which is temporally varying and the part which might be described as "standing eddies"), contribute fluxes of momentum, energy, heat, *etc.* which provide some of the pathways not found in the simple time-average fields (Rhines, 1977).

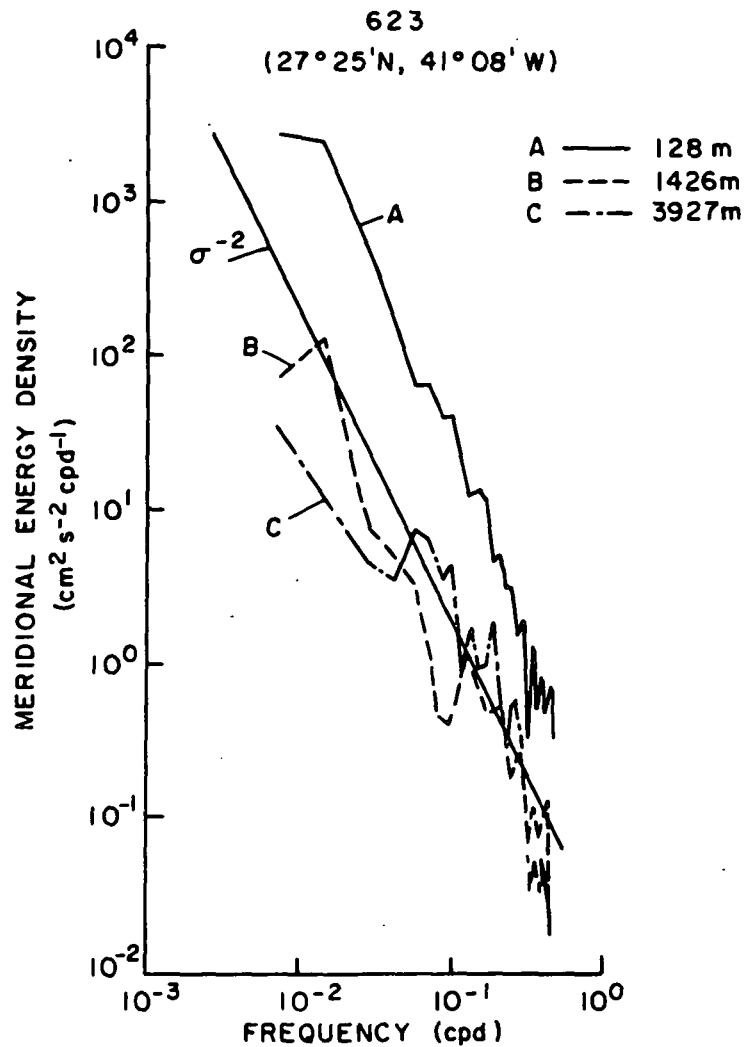


Figure 2.3 A typical frequency spectrum of the north-south component of velocity in the central North Atlantic measured by moored current meters (from Wunsch, 1981a).

## 2.2 The Character of Oceanic Variability

The turbulent nature of ocean currents, their global extent, their regional and temporal variability, and the interrelationships among all scales of motion, greatly complicate studies of the circulation. The temporal variability of the ocean has been measured at a variety of locations in the ocean, particularly in the Western North Atlantic. Figure 2.3 displays the frequency spectrum from one-year-long current-meter measurements in the mid-North Atlantic. It is reasonably typical of open-ocean spectra in being quite "red"; that is, the energy density increases with decreasing frequency. The redness has two important consequences. (a) A one-year record is insufficiently long to determine a weak mean, *i.e.* time-averaged flow. The one-year time-averaged velocity of the record at 128 m was 18 cm/s and is not statistically significant. Thus the duration of a mission to determine the time-averaged ocean circulation at a point is several years at least. A real average is probably attainable over long time spans which are difficult to calculate *a priori*. (b) The nearly -2 slope of the spectrum at high frequencies implies that a formally aliased measurement will show significant contamination only near the Nyquist frequency (see Wunsch, 1972). The spectrum of longer-term variability in the same region (figure 2.4) shows a flattening or plateau occurring at around 100 days, a

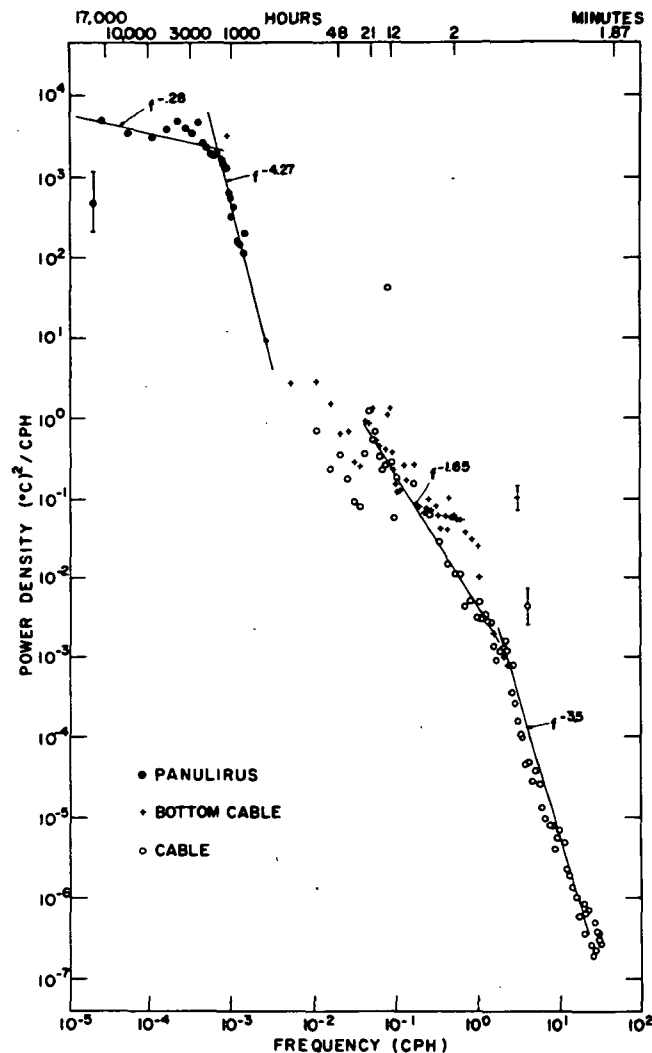


Figure 2.4 Frequency spectrum of variability of temperature in the main thermocline near Bermuda. Note that the variance is due almost entirely to fluctuations with periods greater than 40 days, and that the spectrum tends to be flat at these periods (from Wunsch, 1972).

feature that corresponds to the mesoscale eddy field studied by The Mode Group (1978) and others. As one penetrates deeper into the ocean, the spectrum tends to increase much less steeply toward lower frequencies in the very deep water.

The vertical structure of the motion tends to be dominated by the lowest modes, that is, by the barotropic mode (having velocity independent of depth with no signature in the density field) and the first baroclinic mode (having one reversal in direction with depth in the horizontal velocity) with a strong density signature appearing as a gross movement up or down of the main thermocline.

The spatial variability of the ocean is less well known. Most of the data (e.g., Katz, 1973; Gordon and Baker, 1980; Wunsch and Gaposchkin, 1980) suggest a nearly white velocity spectrum, at scales larger than the deformation radius, with possibly an excess at wavelengths around 200 km, corresponding to the mesoscale eddy field. It may be true that at sufficiently small wavenumbers the motions become more steady and dominated by the time-mean circulation which has a definite tendency to zonality.

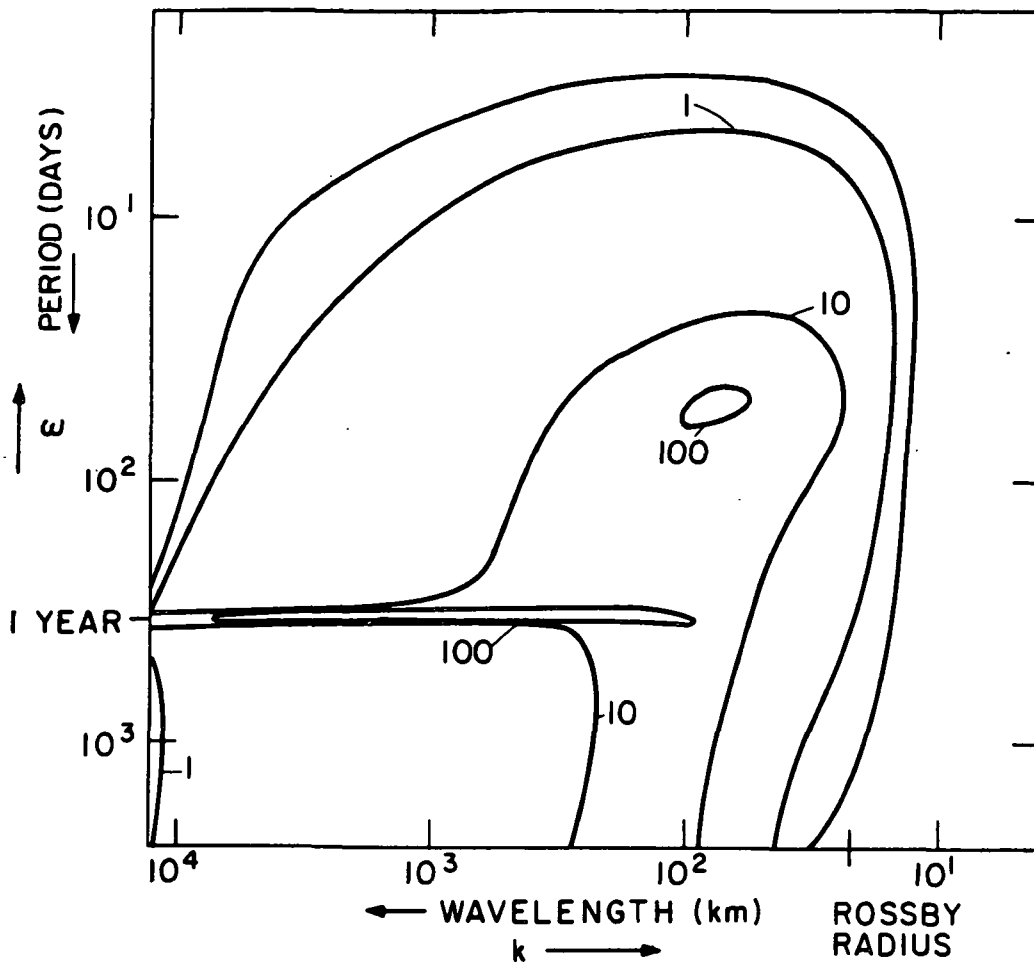


Figure 2.5 Sketch of the frequency-wavenumber spectrum of the general circulation at mid-latitudes, with arbitrary contour units.

By combining the general observations on temporal and spatial variability, we can sketch (figure 2.5) the outline of the frequency-wavenumber spectrum of the general circulation of the ocean, a sketch that will be useful for the following discussion of strategies for sampling the ocean. The peak near 100 days and 100 kilometers is due to mesoscale eddies, and the ridge at one year is the annual variability which can be found at many wavelengths. Little variability is expected at scales smaller than the Rossby radius of deformation, or at high frequencies, but considerable variability is expected at long periods. All these sweeping generalities must be modified in detail in the presence of bottom topography, proximity to strong mean flows, and oceanic boundaries. In the vicinity of the Gulf Stream (and by inference the Kuroshio and other western boundary currents) the eddy band becomes considerably more intense and tends to shift toward somewhat-shorter periods (*circa* 50 days; Schmitz, 1978). When strong currents are channeled, as in the Florida Current (Duing and Mooers, 1977), and the Circumpolar Current through the Drake Passage (Nowlin and Pillsbury, 1981) the spectra have strong motions at periods of 3-20 days. On the equator (Wunsch and Gill, 1976) velocity and hence sea level also tend to have considerable energy at periods between 2 and 30 days. These special regions are, in terms of geographical area, a small fraction of the world ocean, but they are kinematically and dynamically important.



### 2.3 Observational Problems

Historically, oceanographers have had to observe the world's oceans from a few slow expensive ships. In more recent years, they have managed to develop *in situ* measuring systems able to last for a year or longer. But these latter instruments are far too few to measure the entire globe with adequate resolution.

Working from their ships for the past century, and measuring the density field as described above, oceanographers have built up a gross picture of the large-scale circulation of the ocean based on the geostrophic relationship. There are two extremely serious problems with the resulting "classical" picture. Because of the difficulty of sampling a global fluid from a ship, the inferred flow is potentially badly aliased by time changes. All observations have to be lumped together as though they were contemporaneous ("synoptic"). The problem is mitigated somewhat on the large scale by the evident "redness" of the frequency spectrum, but as noted above, the smaller scales are dynamically and kinematically related to the larger scales.

The other major problem with the present picture is the absence of the "integration constant" that appears in (4). Because there has been no way to determine long-term average absolute flows at any depth from ships, the constant is based on an educated guess—usually that at some great depth in the ocean there is a level at which the absolute velocity vanishes (see figure 2.2). This reduces the problem to the notorious "level-of-no-motion" controversy. Although some progress has been made very recently in dealing with this problem, there is no generally accepted procedure that has been applied (or is applicable with existing data) to the global problem.

As a consequence of these difficulties, existing ideas about the general ocean circulation are at best semiquantitative. The lack of a quantitative picture is one of the greatest stumbling blocks to progress in understanding the ocean circulation and its possible changes.

Of course, it may be possible to determine the absolute flow fields and time-averaged quantities by deploying modern recording current meters in the ocean. There are two major difficulties with actually doing this. To measure circulation changes on spatial scales of order of a few hundred kilometers would require an impossible number of spatially independent observations. Second, in most regions of the ocean the energy of the small-scale temporal variability exceeds that of the time-averaged variability by one or more orders of magnitude. The spectrum of the variability is such that at many locations it takes several years of data to obtain a stable mean velocity.

Furthermore, the discovery of this intense eddy field, which dominates the velocity records, means that one must attempt to understand its character globally. As noted above, the time-dependent fields can have time-averaged effects through the nonlinear equations of motion. With existing equipment we have obtained only a fragmentary picture of this global variability for short periods of time in restricted regions of the oceans.

### 2.4 Deviations from Geostrophy

The ocean differs from geostrophic balance in a number of ways, and it is useful to have some understanding of how this occurs. As already noted above, pure geostrophic balance is not possible, even in principle, because it does not allow for sources and sinks of energy. Most of the large-scale flows we have discussed (*i.e.* flows on the scale of the Rossby radius of deformation and larger) are really what is called quasi-geostrophic. In a sense that can be made specific and quantitative, they differ slightly from geostrophy. Both theory and observation show, however, that one cannot observe the small imbalances due to the missing dynamical terms in equations 1 and 2 by directly comparing the pressure force with the Coriolis force. Normally these missing dynamics can only be observed indirectly by computing higher-order quantities

(essentially derivatives of the lowest-order fields) which eliminate the zero-order balance of geostrophy in the vorticity equation. This has been done on occasion under special conditions (e.g., McWilliams, 1976), but normally it is a very difficult problem.

The most obvious demonstration of deviations from pure geostrophy in the open sea is the evolution of the velocity field with time, implying that there are missing time-dependent terms in the momentum equations 1 and 2. But it is still true that at any particular time the balance is dominated by the Coriolis and pressure forces, with the missing acceleration terms being a small residual.

Direct observation of non-geostrophic balances is possible under some restricted circumstances. In regions like the high-speed core of the Gulf Stream, the *downstream* balance tends to be measurably non-geostrophic. For example, it is possible to observe the "Bernoulli head" (the Gulf Stream flows downhill) along the coast of the United States. This is a manifestation of missing nonlinear terms in the momentum equations. Theory (Charney, 1955) also requires them. But it remains true that the cross-stream balance, involving the Coriolis force from the dominant downstream flow remains geostrophic to high order.

Another region where geostrophy is not expected to apply at first order is in the immediate vicinity of the equator, where the Coriolis force vanishes. But geostrophy does apply to a surprisingly low latitude (2 or 3 degrees), although the observational accuracy required to make use of it increases considerably. Right on the equator where the Coriolis force vanishes, the pressure force is balanced by nonlinear (or time-dependent) terms in the equations of motion. Given the pressure force, one can of course use it in the equations of motion to infer the velocity field as is done with geostrophy, although the relationship is more complex. The equatorial region also has a somewhat different dynamical balance governing the strongly time-dependent flows and must be treated as a special region (the sampling problem is discussed below).

## 2.5 Surface Layer

The ocean circulation is driven primarily by the wind stress at the surface of the sea and by convection resulting from the exchange of heat with the overlying atmosphere and from direct solar radiation (the secondary forcing results from evaporation and precipitation). With the exception of a few small, localized (but extremely important) regions of deep thermal convection, the coupling of the atmosphere and the ocean, and the absorption of radiation, occurs in a thin surface layer approximately 100 meters thick. This boundary layer is non-geostrophic, but as noted, the pressure gradients within it are dominated by the geostrophic flow beneath. But the oceanic circulation and its variability will only be understood completely when the forces acting at the surface are understood as well. In section 2.7 we will therefore briefly discuss the importance of the determination of the wind field over the sea.

In the immediate vicinity of the sea surface the water velocity tends not to be in geostrophic balance; rather the flow responds to turbulent stresses associated with the wind and surface waves. These effects are usually confined to the boundary layer; but it can be shown that the pressure field at the surface (represented by  $\partial\zeta/\partial x$  in equation 2) remains in balance with the geostrophic flows. Thus pressure gradients associated with the geostrophic velocities, which only become the dominant velocity below the surface boundary layer, do penetrate right through the boundary layer and are visible at the surface.

## 2.6 Miscellaneous Non-Geostrophic Flows

On short time scales there are other important flows which do manifest themselves as surface pressure gradients without geostrophic balance. Among these we can list tsunamis, which are long gravity waves, storm surges and tides. Storm surges are a shallow water phenomenon and are discussed later in appendix C.2 under coastal

problems. Tsunamis are short lived and also of significant amplitude only in shallow water. Tides are important, and are discussed below.

## 2.7 The Wind Field

The ocean is driven by the wind stress and the thermodynamic forcing of the sun and atmosphere; but even the latter involves the wind field because the downward mixing of heat in the surface layers and the evaporation of water are strong functions of wind speed. Determination of the frequency and wavenumber character of the wind stress over the open sea is therefore a major goal of oceanographers as well as of meteorologists, for whom it provides the lower boundary condition on their circulation models. At present, knowledge of both the time-averaged and of the variable wind field is very crude (figure 2.6), and is based largely upon reports from merchant vessels, reports of often dubious reliability. Worse, the ships tend to avoid the regions of highest winds, regions of greatest interest to our problem, with the cumulative result that existing charts of wind stress do not agree even qualitatively. Quantitative studies of the oceanic circulation, which depend on the curl of the wind stress in mid-latitudes, place even more severe demands on the accuracy of the wind fields. Lastly, computations of oceanic variability require that the equivalent variability of the wind field must be known globally with an accuracy equal to that expected from the computations.

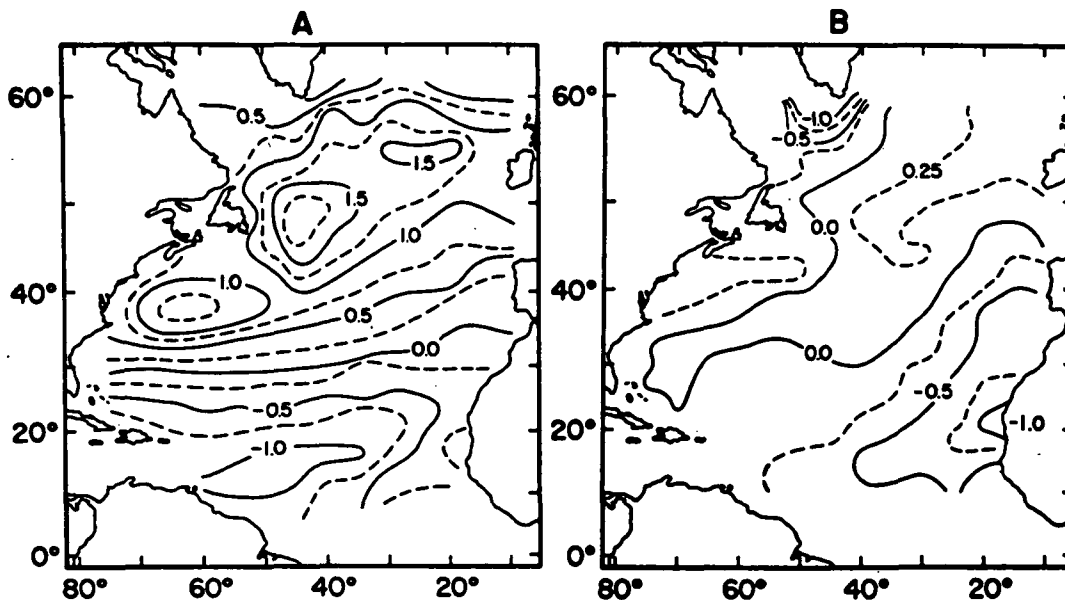


Figure 2.6 (A) Contours of annual mean eastward stress over the North Atlantic in units of dynes per square centimeter. (B) Contour of annual mean northward wind stress (from Leetmaa and Bunker, 1978).

## 2.8 Interaction of Waves and Currents

Ocean waves propagating into regions of opposing currents and into shallow water are shortened and steepened. Typically this is of only minor importance and occurs in coastal areas where incoming waves meet shoals and locally strong tidal currents. But in a few regions waves of much greater importance are produced. Along the east coast of South Africa, the southward flowing Agulhas Current meets large storm waves coming up from the southern ocean, steepening and focusing them. Both influences combine to produce monster waves capable of severely damaging or sinking large

supertankers (Dawson, 1977). One such wave caused \$1,200,000 damage to the tanker "Wilstar" (132,700 tons) in 1974, while another sank the "World Glory" (48,823 tons) in 1968 (Mariners Weather Log, 1974). Other monster waves have been recorded along the Greenland continental shelf, along the north edge of the Gulf Stream, near Ushant at the approaches to the English Channel, and off the northwest coast of India.

The regions where giant waves occur, and the general conditions resulting in such waves are known and described in the appropriate "Pilots," but the exact mechanisms are not understood well enough to predict accurately the occurrence of the waves. In particular, the relative influence of bottom topography and currents in influencing long steep waves remains to be determined. Further investigations will require detailed observations of waves and currents over scales of 100-1000 wavelengths (20-200 km) for use with existing theories of wave-current interactions. Especially needed are velocity profiles across the particular current system near the times they encounter long steep waves, maps of bottom topography, and observations of wave heights.

## 2.9 Tides

Tides are periodic motions of the ocean and the Earth at frequencies precisely known from the gravitational forcing of the moon and sun. They arise directly from the gravitational forcing and indirectly from atmospheric tides, solar heating, and land-sea breezes, the latter being known as the radiational tides. For the solid Earth, a distinction is made between that portion of the tide which is directly forced by the gravitational attraction of the moon and sun and that which is due to the flexure of the Earth due to the weight of the ocean tide; and satellite altimeters measure the sum of the ocean and the earth tide.

Although the ocean tide is forced by low-order spherical-harmonic perturbations in the gravitational field (dominantly the second spherical harmonic), the result is a wave motion containing shorter scales. Thus the ocean tide is not a bulge following the moon and sun, but rather it is a long wave profoundly modified by the rotation of the Earth. Added to this is the relatively small radiational tide which, for example, contributes a few percent to the total tidal signal along the coasts of North America (Zetler, 1971).

In contrast to the oceans, the solid-earth tide responds nearly elastically and closely follows the gravitational forcing. A small deviation from elasticity of perhaps 10% is due to the oceanic loading; nevertheless the influence of the ocean tides extends far inland and can be detected over most continental areas. In principle there should also be a lag caused by dissipation in the solid earth, but it is yet to be measured, partly due to interference from the ocean-loading tide.

Tidal signals appear in many geophysical measurements; and have many important influences. For oceanography, (a) tidal dissipation could influence the ocean circulation (Hendershott, 1981); and (b) tides couple with Earth's magnetic field to produce variations in Earth's electric field.

For geophysics, a precise knowledge of the ocean tides would allow the structure of the ocean tide to be used as a known function to be convolved with earth structure. Depending on the intermediate dynamics, the resulting geophysical signal can be used to infer properties of the solid earth. The tidal signal also appears in measurements of gravity, tilt, and strain; and improved knowledge of the tides will result in more accurate measurements of these quantities.

For astronomy and space physics (see Lambeck, 1980), the tides are an important factor in: (a) station locations in three dimensions relative to Earth's center; (b) Earth's moment of inertia and hence the length of the day; (c) the secular retardation of the rotation of Earth; (d) measurements of polar motion; (e) satellite positions, both periodic and secular; and (f) the deceleration of the lunar longitude. (Whether or not

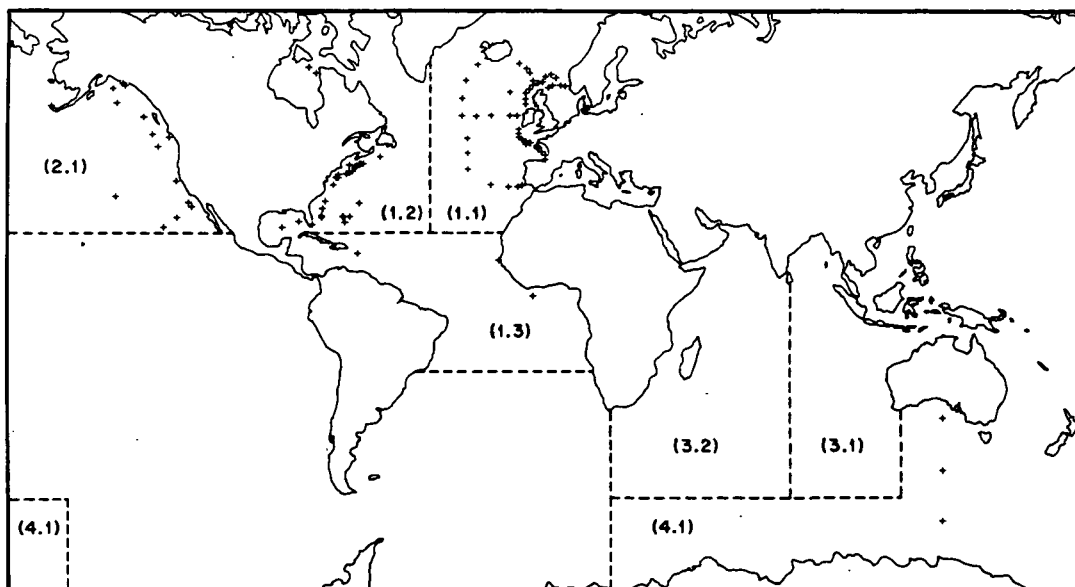


Figure 2.7 Global distribution of pelagic tide-gauge stations compiled by the International Association for the Physical Sciences of the Ocean. Note that the deep-ocean tides have been measured in only a few places, hence our knowledge of tides depends essentially on numerical computations constrained by island and coastal measurements. Since this figure was compiled, a few additional observations have been obtained in the western Indian Ocean and in the Antarctic (from Cartwright, Zetler, and Hamon, 1979).

all of the deceleration can be explained by tidal dissipation is of importance to geophysics and to the history of the evolution of the solar system.)

Observations of tides by coastal gauges have been made continuously for hundreds of years. Extrapolations of these measurements to the deep sea were initially empirical, *e.g.*, the M2 charts by Harris (1904) and Dietrich (1944). More recently the tides have been estimated by direct numerical computations (see reviews by Hendershott, 1977 and 1981; Cartwright, 1977; and Schwiderski, 1980). The best of these computations make extensive use of measurements both along the coasts and in the interior of the ocean. Unfortunately, most coastal measurements are in awkward locations for use with deep-sea tidal models. Besides being on the "wrong" side of the continental shelves, coastal measurements are usually taken in bays, estuaries, or up rivers where the tidal signal is strongly disturbed by the intervening shallow water. Even island gauges are usually in harbors or lagoons, and lags of as much as one hour are possible between such a gauge and the surrounding deep-sea tide. To avoid these problems, the astronomical ocean tide is now measured directly by bottom pressure gauges (Cartwright *et al.*, 1980); but the distribution of these measurements in the deep ocean is still poor (figure 2.7).

Because nearly all good tidal observations have been used to compute the tidal charts, it is difficult to obtain independent estimates of the accuracy of the charts. However, what data exists, indicates that tides in deep water may not be known with an accuracy of better than ten centimeters in many areas.

### 3. Geophysics

The usefulness of altimetric measurements for geophysical studies has been reviewed in reports by the National Research Council (1978, 1979b); they find that such measurements can make major contributions to geophysical problems. Although the main concern of this report is the influence of the solid earth on ocean topography, the geophysical applications are so important they warrant at least a brief summary.

The height of the sea surface relative to the center of the Earth is a function not only of ocean dynamics but also of the distribution of mass within the Earth. In fact, the latter dominates, producing changes in height that are roughly 100 times those due to surface currents, and thus altimetric observations of sea level are useful for the study of the interior of the Earth.

If the waters of the ocean were still, and all external forces were removed, the sea level would correspond to the geoid, a surface along which the gravitational potential is constant. Typically, this surface undulates by up to a hundred meters relative to a reference ellipsoid, and the undulations have wavelengths ranging from a few to thousands of kilometers. The external forces acting to move this surface are primarily tidal plus the gravitational attraction of the atmosphere and atmospheric pressure. Together with the ocean currents, these produce undulations of a meter or less, and satellite altimeters observe primarily the geoid and only secondarily other geophysical processes such as ocean currents and tides.

Studies of the gravitational field near seamounts on the ocean floor indicate that the lithosphere behaves as a thin elastic plate riding on top of a more fluid substratum. The plate supports the load of the seamount over distances of a few hundred kilometers, but beyond this distance it bends and the weight of the seamount is compensated by buoyancy forces under the plate resulting from its sinking. The compensation is observed by noting the ratio of the strength of the anomalies in the gravity field relative to the height of the bottom topography. For some distances (near 200 km) that are determined by the thickness and strength of the plate, the ratio suddenly becomes small, and this is an indication of the strength of the plate. For shorter distances, the gravity anomalies and geoid undulations are due primarily to bottom topography, and for greater distances they are due primarily to the distribution of mass below the plate. Both can be studied using maps of Earth's gravity field.

The geoid observed by altimeters may be used instead of gravity for important aspects of these studies. The Fourier transform  $F_g$  of the vertical component of the gravity field is related to the Fourier transform  $F_N$  of the geoid height by the simple equation:

$$F_N = \frac{1}{g|k|} F_g$$

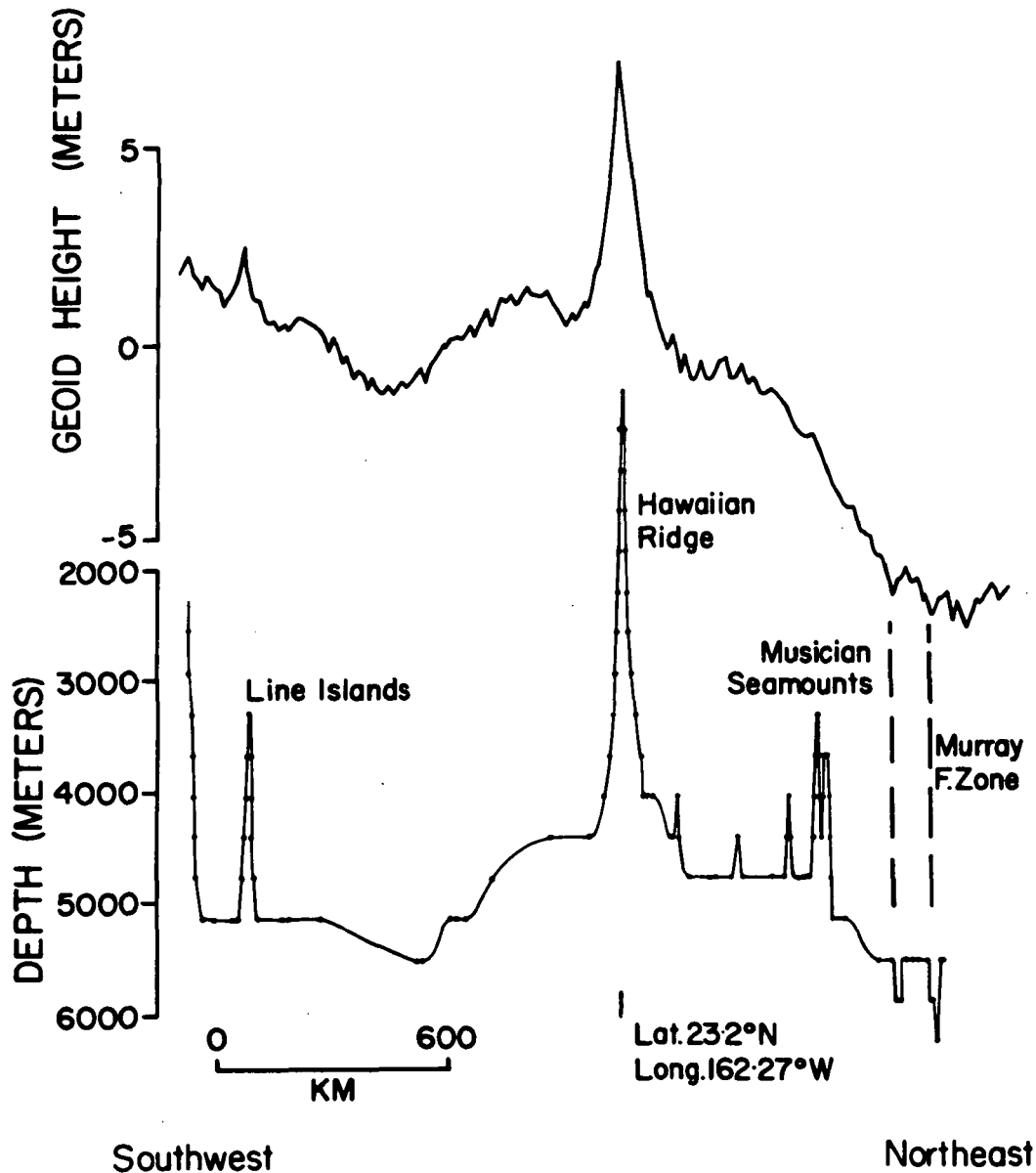


Figure 3.1 Height of the geoid measured by an altimeter on Geos-3 and the corresponding bottom topography along the subsatellite track. The geoid profile has had a regional geoid subtracted from it to emphasize the influence of the bottom topography (from Watts, 1979).

where  $g$  is the normal gravity ( $9.8 \text{ m/s}^2$ ) and  $k = 2\pi/\lambda$  is the wavenumber associated with undulations of wavelength  $\lambda$  (Chapman, 1979). Thus geoid anomalies have nearly the same shape as gravity anomalies, but the geoid tends to smooth short wavelength features and accentuate longer features.

### 3.1 Bottom Topography

The lithosphere is relatively rigid over distances of a few hundred kilometers, and changes in sea-floor topography produce corresponding changes in the shape of the geoid (figure 3.1). Subsea mountains and seamounts are particularly prominent, the latter producing changes in elevation of one to ten meters in the geoid over distances of

tens of kilometers, and maps of geoid height with resolution of ten to twenty kilometers can be used to map the distribution of subsea features.

Maps of seamounts are important to geophysics and oceanography:

(a) The total volume of seamounts is an indication of igneous activity, and they may account for a significant portion of the total production of igneous rocks on Earth.

(b) Seamounts disturb the flow of ocean currents producing large-amplitude internal waves directly over the mounts. These waves influence the propagation of sound in the ocean, and probably contribute to mixing between surface and deeper layers.

(c) The uncompensated weight of undersea mountains near ridge crests produces stresses which tend to push the ridge crest apart (Parsons and Richter, 1980), and may contribute to spreading at ridge crests.

Despite the importance of these bottom features, they have been poorly mapped in many regions. Seamounts in particular are very small, and are not seen except on those rare occasions when a ship happens to pass directly over the mount. Satellite altimeters are beginning to fill these gaps in coverage, but many regions will remain unmapped until more altimeter data are collected.

### **3.2 Mantle Convection**

The new paradigm of plate tectonics is founded on the observation that the lithosphere moves as a connected system of rigid plates. The forces which drive the motion are unknown, but convection in the mantle is thought to play a major role. Laboratory studies and theory suggest that the convection consists of a series of connected cells of warm rising material interspersed with regions of cool sinking material with typical cell size on order of 1000 km. Density is controlled primarily by temperature, and the variations in density should produce variations in the height of the geoid (McKenzie, 1977). Certainly the regional features observed in the oceanic geoid must be due to deeper structure below the lithosphere and they may be related to mantle convection and other processes which could drive lithospheric plates.

### **3.3 Rigidity of the Lithosphere**

The admittance function, relating undulations of the geoid to undulations of bottom topography, is a function of the strength, thickness, and density of the lithospheric plate supporting the weight of bottom features such as seamounts; and the admittance is used to constrain estimates of lithospheric rigidity (Watts, 1979). The problem is underdetermined, and solutions using geoid information alone are not unique. When combined with other (seismic and geochemical) information about the lithosphere, the geoid can give useful information about the strength of the lithosphere and its response to loads.



#### 4. Satellite Altimetry

An altimeter that could measure the shape of the sea surface with sufficient accuracy and precision and that could be placed in orbit around the Earth would have an enormous impact upon many of the major problems of oceanography and geophysics. But, making practical use of realistic altimetric measurements presents a number of complex issues which must be understood in order to evaluate the benefits of a real system.

We have seen that a measure of the surface pressure field of the ocean provides the surface geostrophic velocity, and that this is the oceanographer's missing integration constant. Because of the global coverage possible with a satellite, many of the aliasing problems which plague shipborne work would disappear. But altimetric measurements themselves have many sources of error which are a complex function of position and scale. Thus we must examine in detail the extent to which spacecraft can provide the requisite information. Furthermore surface pressure gradients, even if measured perfectly, can only provide surface geostrophic currents (and tides). Although these are of considerable interest and use in themselves, the ultimate justification for the expense and trouble of a full-scale space mission rests on the ability to translate these surface measurements into statements about the structure of the complete flow field—from top to bottom.

The altimetric measurement itself involves several physical variables. An ideal radar altimeter measures the distance from a spacecraft to an ideal sea surface. Translation of this measurement into a sea surface slope involves further calculations.

First, the absolute height of the spacecraft itself must be known; and this requires both a tracking system or systems, and mathematical models of spacecraft dynamics. These latter require the gravitational field of the Earth, which is imperfectly known, but constant, as well as adequate models of the forces due to the drag of the atmosphere and radiation from the sun and the Earth, all of which vary in time and space, depending upon the state of the sun and the orientation of the satellite, among other variables.

Second, to convert the absolute shape of the sea surface to an oceanographically useful variable, the shape of the equipotential surface, usually called the "geoid," must be known. This surface varies by roughly 100 m relative to the reference surface, termed the reference ellipsoid. In turn, the sea surface varies as described above only by roughly one meter relative to the geoid. Thus, there is a great premium placed upon determination of the geoid if time-averaged (and hence, total) geostrophic velocities are to be found. On the other hand, if only time-dependent changes in the geostrophic velocity are required, an accurate geoid is not fundamentally necessary, but may still be required in practice (this issue is discussed more fully later in the report).

Third, the altimeter itself is subject to various errors: the precision of current altimeters (such as that on Seasat) is approximately 5 cm (Tapley *et al.*, 1979), but a

number of corrections must be applied to the apparent altimetric height. These include corrections for the amount of water vapor in the atmosphere, and the number of free electrons in the ionosphere, both of which change the speed of electromagnetic radiation and hence of the altimeter pulse. Furthermore, the sea surface is not smooth, rather it is complex, rough, and moving; and the shape of the surface can substantially influence the height measurement.

Finally, relating the surface geostrophic velocity to velocities at depth involves the density field of the ocean below the surface. This cannot be obtained from space but requires direct observation and modelling.

#### **4.1 Error Fields**

The accuracy of satellite measurements of ocean topography can be estimated from experience with measurements made by altimeters on Geos-3 and Seasat. Major errors are due to uncertainty in the knowledge of the geoid (an uncertainty which varies from around a half meter in well studied areas, to around ten meters in remote areas), and orbit inaccuracy, which for existing satellites is on order 0.5-2.0 m in the height relative to the center of the Earth. Tides, surface waves, atmospheric pressure, water vapor in the atmosphere, and free electrons in the ionosphere all contribute smaller errors. These are sometimes small enough to be neglected; sometimes they can be reduced to a level of a few centimeters using additional information.

The time and space scales of the error fields are particularly important. The program seeks to reduce those errors with scales that match the oceanic scales sketched in figure 2.5, but can tolerate errors with other scales—removing them through simple filtering operations.

##### **4.1.1 Geoid Uncertainty**

The geoid must be directly subtracted from the altimetric field in order to yield total instantaneous (as opposed to the time-variable component) geostrophic velocities. For the time-variable components a good geoid is required only if the orbits fail to repeat their ground tracks with a very high degree of accuracy. Rough estimates of the longer wavelength components of the geoid, up to degree and order 10-15 in its spherical harmonic expansion, are known globally from the accurate tracking of the orbits of many different satellites over long times (King-Hele, 1976). Shorter-wavelength components are known by combining worldwide measurements of gravity, shipborne gravity surveys of particular regions, and the geoid measured by satellite altimeters (Rapp, 1980a). But the contribution of the movement of water to the shape of the sea surface is neglected at the level of accuracy achieved in these computations. That is, the sea surface is assumed at lowest order to be the geoid. Nevertheless, it appears that spaceborne techniques will always be limited to accurate determination of the geoid over wavelengths longer than some critical value on order several hundred kilometers. Shorter wavelength components can only be determined regionally using geoids built up from shipboard measurements (*e.g.* Marsh and Chang, 1978). In the future, accurate tracking of the distance between two low satellites (the current Gravsat concept; National Research Council, 1979b; Douglas, Goad, Morrison, and Foster, 1980) or by other techniques will improve our knowledge of wavelengths near the critical value. Ultimately, a combination of altimetric, gravitational, and orbital information could be analyzed *in toto* to yield the best estimates of the geoid, topography, and orbit consistent with the observations.

To examine the accuracy question in more detail, consider the representation of geoid undulation by a spherical harmonic expansion. This expansion can be used to compute two types of a "point" undulation based on a truncated series: either an undulation at a given spherical harmonic degree, or an areal average based on a truncated series. The most recent solution based only on satellite tracking is that of GEM9

(Lerch *et al.*, 1979) which is complete up to degree twenty. At a given degree the geoid-undulation error is small (*e.g.*, 29 cm at degree seven). But the total error, due to errors in all the coefficients, is about  $\pm 1.7$  m when averaged over the Earth. The effect of neglecting higher degree terms is about  $\pm 3.2$  m, for a total error of about  $\pm 3.5$  m. The situation is better when averaged values are used. This yields, for example, a standard error of about  $\pm 2.6$  m for averages over  $1^\circ \times 1^\circ$  ( $111 \times 111$  km) areas as estimated from a comparison of Geos-3 altimeter data with GEM9 undulations.

Improvement in the determination of the geoid can be obtained by increasing the accuracy and number of potential coefficients and/or adding terrestrial gravity data to the geoid calculations. The degree of improvement depends on the number, the accuracy and the size of the areas used. Computations with data from  $1^\circ \times 1^\circ$  areas in well-surveyed regions and with improved geoid-modeling procedures indicate a current achievable accuracy (for a point undulation) of about  $\pm 0.75$  m (Rapp, 1980a) excluding the effects of smaller-sized areas. Much smaller areas are needed in regions where the geoid changes rapidly, as this effect can be on the order of several meters. Even if  $5' \times 5'$  areas are used in the geoid computations, and such geoids are rare, differences between altimetric and gravimetric geoids are still on the order of  $\pm 45$  cm (Torge, 1980). This leads to the conclusion that existing detailed gravity coverage is fairly poor relative to our requirements for a highly accurate geoid (Rapp, 1980b).

Jekeli and Rapp (1980) have discussed some of the geoid undulation accuracies to be expected from a nominal six-month Gravsat mission of two satellites at a height of 160 km whose separation is measured with an accuracy of  $\pm 1 \mu\text{m/s}$ . They find that geoid undulations averaged over areas, should have accuracies of  $\pm 16$  cm for  $30' \times 30'$  areas,  $\pm 3.7$  cm for  $1^\circ \times 1^\circ$  areas, and  $\pm 1.5$  cm for  $2^\circ \times 2^\circ$  areas.

These estimates of accuracy may also be considered as a function of wavelength. For example, at degree 100, which has a half wavelength of 200 km, the undulation accuracy is 0.097 cm. If the error of all the coefficients up to degree 200 is considered, the standard error would be about 0.46 cm (figure 4.1).

The conclusion then is that the currently envisaged Gravsat mission (see sections 5.1.3 and appendix B) could provide a geoid accurate to one to two centimeters when averaged over areas on order two-hundred kilometers on a side. As the area grows, the error in the geoid average drops very rapidly.

#### 4.1.2 Orbit Uncertainty

An altimetric satellite measures its distance above the ocean surface, and the usefulness of the measurement depends on the accuracy with which the center of mass of the satellite can be located with respect to the origin of the geocentric coordinate system, the radial component of the position being by far the most important. For studies of oceanic circulation, the accuracy must be much better than the ocean-surface signature to be determined. Thus the radial component of the orbit must be determined with an accuracy of  $\pm 5$  cm for wavelengths of 10,000 km (TOPEX Precision Orbit Determination Group, 1980) in order to measure oceanic topography with an accuracy of  $\pm 10$  cm over distances of 3000 km. This condition, in turn, translates into the requirement that the error in the radial component of the orbit, with the frequency of once per revolution, must be known with an accuracy of  $\pm 5$  cm.

The accuracy with which the satellite orbit can be computed depends in a complicated way on the accuracy of estimates of the dynamic forces which act on the satellite, and the accuracy and frequency with which the satellite's motion can be observed. The dominant forces are those of the gravitational attraction of the Earth, sun, and moon, the drag of the atmosphere, the pressure due to both direct solar radiation and reflected earth radiation, and the gravitational attraction of ocean tides.

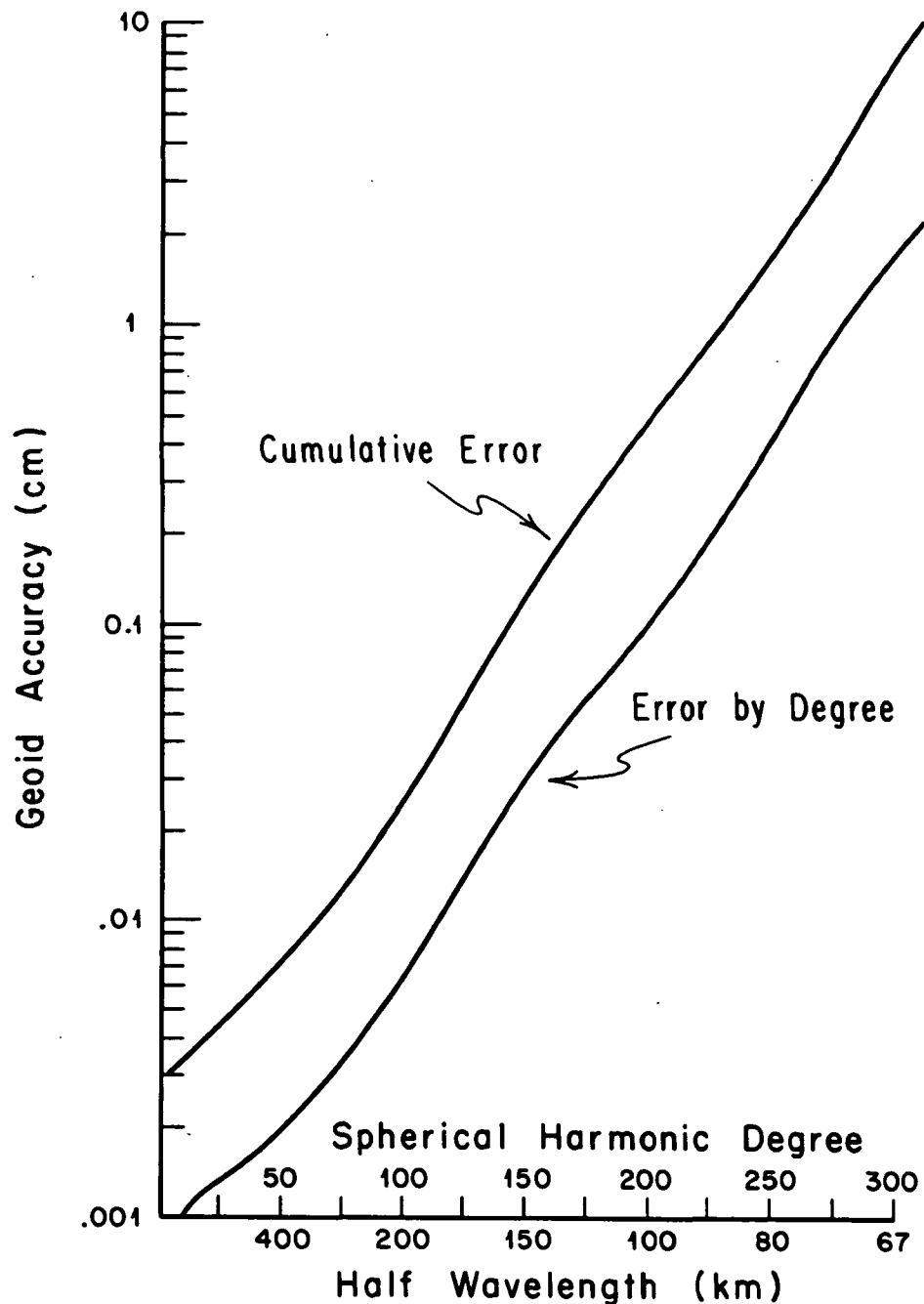


Figure 4.1 Geoid undulation accuracy, by wavelength, for a Gravsat mission having a tracking error of  $\pm 1 \mu\text{m/s}$ , flying at a height of 160 km, and operating for six months.

A complete description of the various effects and their influence on the determination of the orbit is beyond the scope of the present discussion, but the details are given in appendix B. Here it is sufficient to state that gravitational forces and radiation are the dominant sources of error, but that other errors cannot be neglected. If Gravsat produces data with the expected accuracy, not only will the gravitational errors be greatly reduced, but also the influence of radiation could be calculated with improved accuracy. Overall, the Topex Precision Orbit Determination Group (1980) estimates that the radial component of the orbit could be calculated with an accuracy of  $\pm 9 \text{ cm}$ ,

provided that Gravsat data are available, that the satellite is sufficiently dense, that it is in a relatively high orbit, and that it is well tracked.

#### 4.1.3 Tides

The tides not only introduce "errors" into the determination of geostrophic velocity, but they are of considerable interest in their own right. Existing numerical models (Schwiderski, 1980) suggest that, at best, *a priori* corrections good to 10 cm could be made to the altimeter globally; but there are undoubtedly important regions where the errors are larger than this value. A multiyear altimetric mission can improve these values by solving for residual errors in tidal elevation by taking advantage of the properties of their unique frequencies. The degree to which the tidal error can actually be reduced needs to be studied further, but there seems little doubt that the errors can ultimately be reduced to much less than 10 cm over most of the ocean. Because a satellite covers the surface at finite speed, it samples any particular position at comparatively infrequent intervals. Thus the tides are sampled at a frequency much lower than the normal Nyquist criterion for their determination, and any particular tidal line will be aliased into an apparently much lower frequency. This aliasing must be kept firmly in mind in discussions of sampling which follow later in this report. One extreme example should be mentioned here: if an altimetric satellite were in sun-synchronous orbit, as is proposed for several potential non-TOPEX altimetric satellites, then the principal solar tide,  $S_2$ , will be aliased into the mean sea surface topography, making even more difficult the determination of the mean ocean circulation; and the principal lunar tide,  $M_2$ , will appear at a 14-day period. Other tidal lines will appear elsewhere in the sampled spectrum including the annual periodicity. Cartwright (1980) has analyzed the problem of extracting tides from a realistic altimeter mission, and his result will be invoked later when we deal with a specific mission design.

#### 4.1.4 Wave Height

Wave height is of intrinsic interest, particularly to those who operate on the ocean surface, and it contributes an error to the measurement of altimeter height. It is deducible (Walsh, Uliana, and Yaplee, 1978) from the received altimetric radar pulse; and it introduces an error into the estimated position of the mean sea-surface elevation because the troughs of ocean waves tend to be better reflectors than the crests. This results in the centroid of the distribution of returned power being shifted away from mean sea level towards the troughs of the waves. Being able to model and predict the magnitude of this electromagnetic bias is critical to a mission such as TOPEX.

The nature of the problem was investigated using a airborne Surface-Contour Radar (SCR) (Kenny, et al., 1979) capable of observing both returned power and elevation to high accuracy, thus determining the variability of backscattered power per unit area as a function of displacement from mean sea level for various sea states. Figure 4.2 shows histograms of the distribution of sea-surface height together with the distribution of vertically backscattered radio power observed by the radar in 1978. Two different data sets are shown, corresponding to significant wave heights of 1.9 m and 5.5 m, where the significant wave height is defined to be four times the standard deviation of surface elevation. Each distribution is normalized by both the observed standard deviation of the surface-height distribution and by its total area in order that the data may be compared with the normal distribution indicated by the dots. Note that below mean sea level the curves of returned power tend to lie above the curves of surface height, indicating higher backscattered power per unit area. The reverse is true above the mean, indicating lower backscattered power per unit area. The net result is that the positions of the mean reflecting surface is shifted downwards relative to the position of the mean sea surface. A satellite altimeter, which does not have sufficiently high horizontal resolution to resolve scatter as a function of position on a wave, would measure a sea level that is too low because it observes the mean reflecting surface.

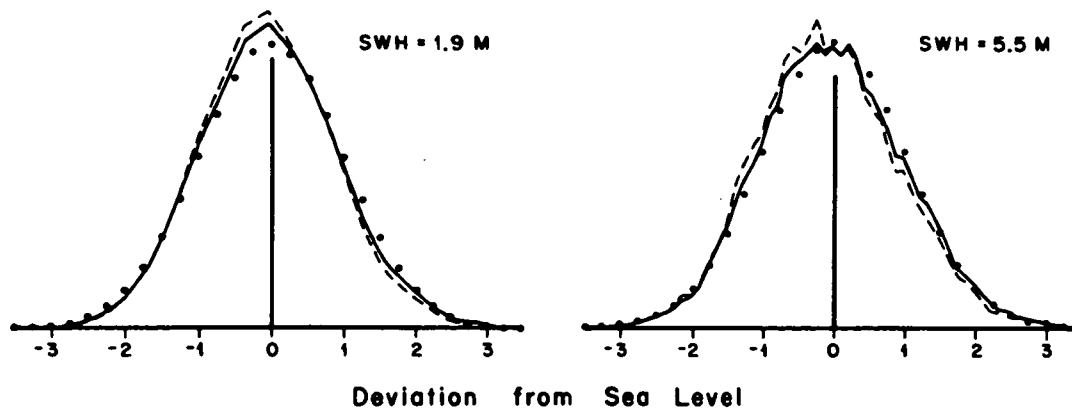


Figure 4.2 Probability density distribution of sea-surface elevation (solid curve), and backscattered power of 36-GHz radio signals (dashed curve), together with the normal distribution (dots). The difference in the centroid of the two curves causes the sea level observed by a radar altimeter to differ from true sea level by a small fraction of the ocean wave height.

The SCR measurements, indicated by the circles in figure 4.3, suggest a bias around 1.5% of the significant wave height. Until recently those data were at odds with 10-GHz observations made at the Chesapeake Light Tower from a height of 20 m (Yaplee, *et al.*, 1971). The data, indicated by the Xs in figure 4.3, have a mean value of almost 5% and a large standard deviation which would make altimeter corrections difficult. The data were also different from Jackson's (1979) one-dimensional theory which predicts a linear dependence of bias on skewness.

These differences have now been resolved somewhat. Recent 10-GHz observations made from a low flying aircraft by Choy and Uliana (private communication) indicate a mean bias around 2% with a much smaller standard deviation than the earlier data. Also, D.E. Barrick (private communication) has developed a two-dimensional theory whose preliminary results indicate a smaller trend with skewness than Jackson's one-dimensional results.

These results are encouraging, but more data are needed, especially simultaneous data at 10 and 36 GHz so that any frequency dependence can be determined. Furthermore, in a set of SCR data acquired in April 1980, a 4.0-meter-high swell produced a bias of only 0.2%. This indicates that wind speed (also measured by satellite altimeters) may be required for accurate estimates of the bias. At present the best estimate of the bias indicates that it is generally in the 1 to 3% of the surface wave height, that it tends to increase with wave height and skewness, but that it is very small for swell. Fortunately, the outlook for being able to predict these various effects is good.

#### 4.1.5 Atmospheric Load

As atmospheric pressure increases and decreases, the sea surface tends to respond hydrostatically. That is, a 1 millibar increase in atmospheric pressure depresses the sea surface by 1.01 cm. This does not apply over times shorter than roughly two days (the ocean does not have time to respond), nor over very long periods (circa one year, where other meteorological effects dominate). Because surface pressure over the sea is not routinely available from spaceborne measurements, it must be inferred from wind measurements and analysis of surface observations. Meteorologists estimate (F. Sanders, private communication) that present surface analyses of atmospheric pressure over the sea are generally accurate to  $\pm 3$  millibars although the error may be much greater in regions such as the South Pacific where there are few ships, or in extreme winter storms. This accuracy is expected to improve considerably in the next five to

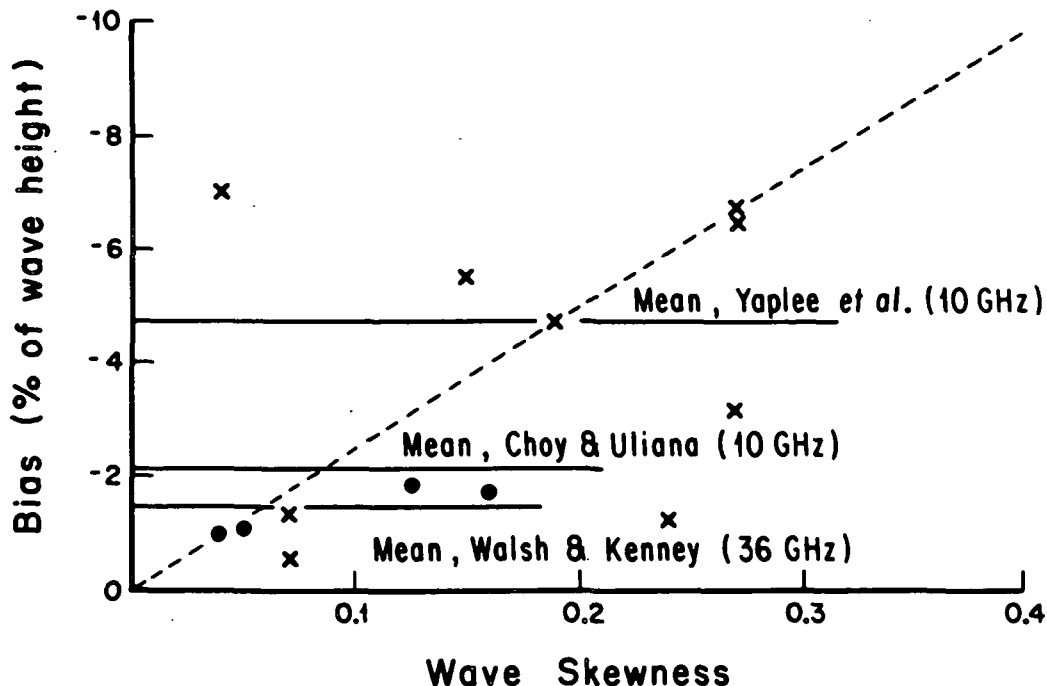


Figure 4.3 Observations and theoretical estimates of the difference between sea level and the level of the surface observed by a radar altimeter, as a function of wave skewness. Experimental observations: X—10 GHz (Yaplee, *et al.*, 1971); O—36 GHz (Kenney, Uliana, and Walsh, 1979). Theory: dashed line (Jackson, 1979). Solid lines are the mean values of all the 36-GHz and 10-GHz experimental observations.

ten years as meteorological data and our understanding of the atmosphere improve as a result of the Global Weather Experiment. In addition, Chahine (1980) has suggested that direct spaceborne measurements of the overlying atmospheric mass may yield surface pressures with an accuracy of 1-2 millibars by the mid 1980's. In any case, the error varies little over distances of hundreds of kilometers, and will not overly influence measurements of oceanic "eddies."

#### 4.1.6 Atmospheric Water Vapor

Water vapor in the atmosphere retards the velocity of radio signals, causing the altimeter to overestimate its height by roughly half a meter, and producing fictitious slopes of the sea surface. Large-scale time-averaged corrections for the influence of water vapor can be made from climatological data. But these are not sufficiently accurate, and local observations are required. The best source of information for correcting the altimeter measurement is the radiation emitted at frequencies near 22.3 GHz by water vapor in the atmosphere and measured by a dual-frequency radiometer on the altimetric satellite.

Estimates of the accuracy of the technique, made by comparing the signal from radiometers with measurements of water vapor made by radiosondes (Moran and Rosen, 1980; Shaper, Staelin, and Waters, 1970), indicate that errors due to water vapor can be reduced to 1-2 cm on average, provided rainy areas are avoided. Additional studies (Goldhirsch and Rowland, 1980; Hollinger, 1980; and Chester, 1981), the latter two based on data from the Seasat radiometer, come to similar conclusions. Furthermore, Chester notes that the error introduced into the technique by radiation from the sea surface due to its temperature and due to foam produced by the wind can

be eliminated using wind speeds estimated from the altimeter (see appendix C.1) and climatological estimates of sea-surface temperature. An interesting by-product is the possibility of computing rainfall rates.

#### **4.1.7 Ionospheric Corrections**

Increasing the free electrons in the ionosphere also decreases the velocity of radio pulses, and this too causes the altimeter to overestimate its height, the effect varying linearly with the number of electrons, and inversely with frequency. Typically, the electron content varies by an order of magnitude from day to night (fewer electrons at night), from summer to winter (fewer during the summer), and as a function of the solar cycle (fewer during the solar minimum), Davies (1980). These variations produce an apparent change in height of 2-20 cm at 13 GHz, the frequency used by the Seasat altimeter. These variations in electron content have wavelengths of many thousands of kilometers and periods of a few hours, with most of the variability concentrated at a cycle per day and a cycle per year, although shorter-scale features may be caused by ionospheric waves and turbulence. Maps constructed by Davies (1978) and Davies *et al.* (1977) for near solar-minimum conditions have been translated by Goldhirsh and Rowland (1980) into error gradients as large as 2 cm per 100 km for the 13.5-GHz altimeter. During a solar maximum these gradients can increase to 4 cm per 100 km.

The magnitude of the ionospheric range error may be estimated using Faraday rotation techniques, such as was done for the Seasat altimeter; but the techniques have two important limitations. First, the instruments used do not directly measure the electron content but must assume a constant magnetic field in order to calculate the electron content. Secondly, the ground-based measurements are sparsely located and spatial extrapolation is necessary, resulting in an inaccuracy as high as 50% (Klobuchar, 1978).

The ionospheric effects can be greatly reduced by using a higher-frequency altimeter (figure 4.4). But higher frequencies are much more rapidly attenuated by atmospheric water vapor and rain. In addition the present instruments that can operate at frequencies as high as 35 GHz comprise the overall design, thus leading to stringent constraints on satellite pointing and transmitter power.

A two-frequency altimeter appears to offer a more nearly optimum solution. With this approach the standard 13.5-GHz altimeter is augmented with a lower-frequency system (*i.e.*, 6 GHz). Because the ionosphere affects these two frequencies differently (figure 4.4), the two range measurements can be used to compute both the height of the satellite and the electron content in the ionosphere. This technique avoids the inherent errors of extrapolation and is expected to reduce the ionospheric uncertainty to the order of a centimeter. In particular, Goldhirsh and Rowland (1980) find that a two-frequency altimeter has a residual standard error of about 0.5 cm due to the influence of the ionosphere.

#### **4.2 The Velocity Field at Depth**

An altimetric mission would not operate in a vacuum; rather it will provide information in the context both of existing knowledge of the ocean and of nonsatellite measurements made in addition to it. The question of what ancillary measurements must be made to maximize the usefulness of an altimeter in space will be addressed later. At this point it is sufficient to note that a mathematical formalism (Wunsch and Gaposchkin, 1980) exists for handling altimetric and geodetic data in conjunction with existing or specifically acquired hydrographic data. Such a formalism is important because it can handle the potential instability in relating surface geostrophic velocities to the field at depth.



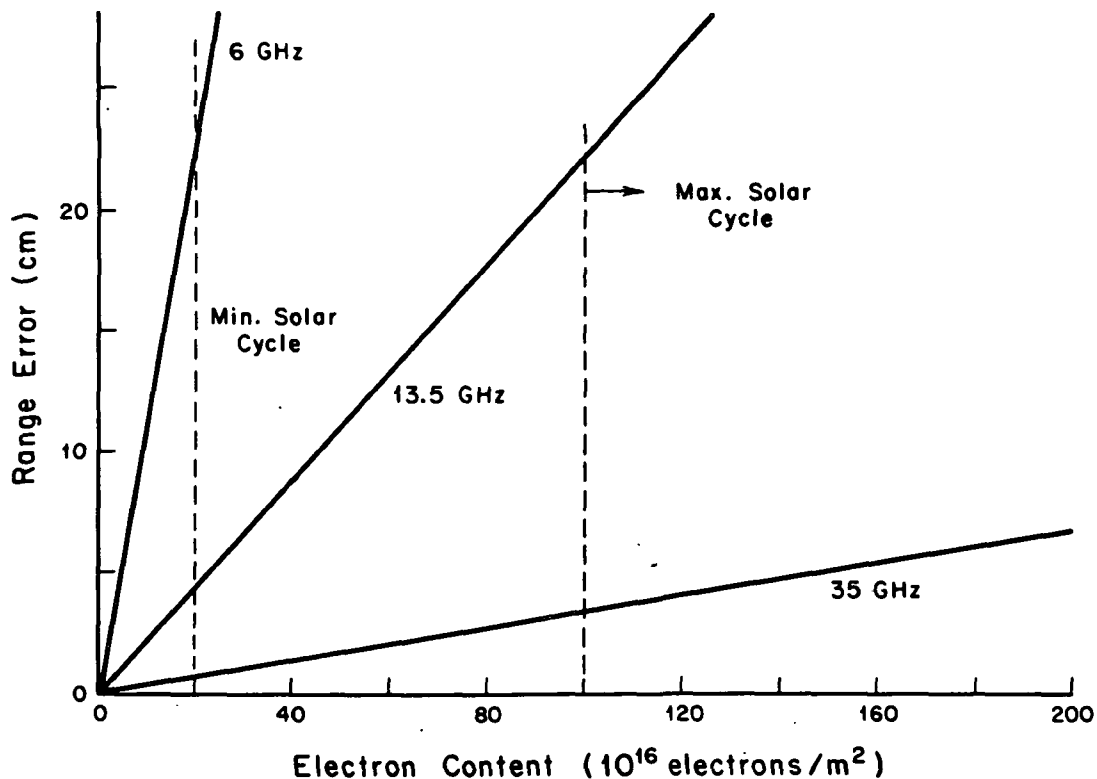


Figure 4.4 Change of range observed by an altimeter operating at frequencies of 6, 13.5 and 35 GHz, as a function of electron content in the ionosphere.

The problem can be summarized by noting that the naive application of equation 5 with the reference level at the surface of the sea puts an enormous premium upon the accuracy of the measurement of *in situ* vertical shear for extrapolation at depth. This problem occurs because the shear tends to decrease with depth. If equation 5 is interpreted as a formula to extrapolate the surface velocity to arbitrary depths, it will incur potentially very large errors far from the surface. The remedy, as Wunsch and Gaposchkin (1980) demonstrate, is to use hydrographic data with a reference level at depth. Through inverse methods, this effectively predicts the surface geostrophic velocity; and the prediction is then corrected by the altimetric data within the error budgets of hydrography and altimetry to yield a consistent, stable system.

#### 4.3 Summary

The primary impediments to making accurate measurements of sea-surface topography using satellite altimeters is the inaccuracy in the computations of the satellite's orbit and in the existing knowledge of the undulations in the geoid relative to a reference ellipsoid. Other sources of error are less important, but cannot be neglected.

The errors are not uniformly distributed in frequency or in wavenumber, and their general influence is sketched in figure 4.5 superimposed on the sketch of oceanic variability. Some scales of variability will be obscured or perhaps even be unmeasurable, while others, particularly the energetic region of the spectrum, may be measured with useful accuracy. Ultimately, the value of satellite altimetry will be determined by the accuracy of techniques for reducing the measurement errors having wavelengths and frequencies that coincide with the most important regions in the spectrum of oceanic circulation.

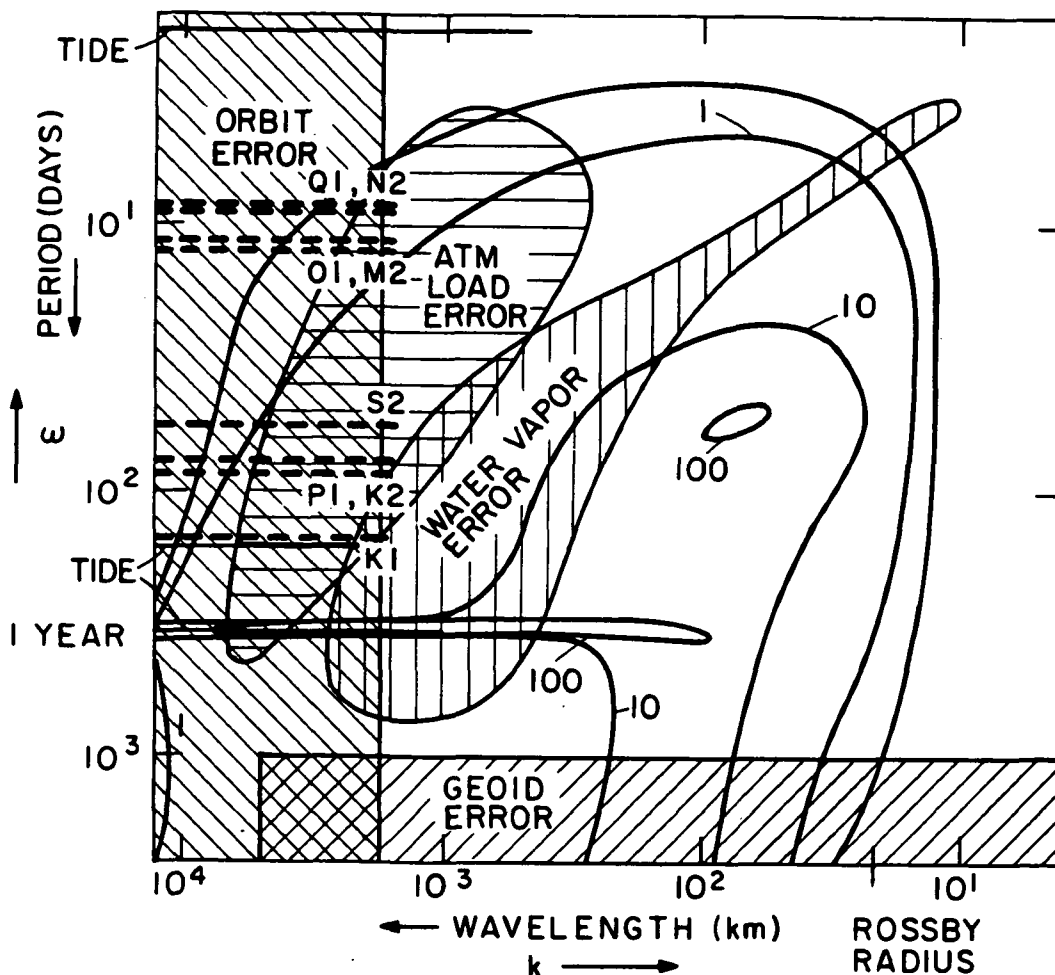


Figure 4.5 Qualitative sketch of the frequency-wavenumber spectrum of the dominant errors in altimetric measurements of sea-surface topography. The dashed lines are the positions of aliased tidal signals that would result from an altimetric satellite in an orbit 1300 km high and having an inclination of  $65^\circ$  (the letters denote the dominant tidal constituents at these frequencies). Not included on the figure are errors due to wave height; these probably will be distributed over the whole plane. It is argued in the text that most of these errors are correctible.

The existing studies of the various sources of error suggest that there is no major obstacle to obtaining a single-pass accuracy and precision of 10 cm over distances of 3000 km and shorter (apart from the geoid error). This figure will thus be used as a simple summary number in the following discussions. As the arc lengths grow much beyond 3000 km, the orbital errors increase and maintaining a 10-cm single pass accuracy across ocean basins requires special tracking measures. Geoid errors, assuming the existence of Gravsat, can be made negligibly small (below 2-cm standard error) over distances of 200 km and longer. With these estimates of the errors, the usefulness of an altimetric mission can be discussed in the next sections.

## 5. An Ocean Topography Experiment (TOPEX): Scientific Rationale

The preceding discussion of the various physical variables, the extent to which they affect determination of the absolute sea surface, and the degree to which they can be accounted for either by measurement or modelling has led the Science Working Group to conclude that a dedicated altimetric mission deserves serious consideration. This mission, called the Ocean Topography Experiment, or TOPEX, is described in what follows in this report. In the present section, we wish to outline the general scientific role of such a mission with due consideration for how the constraints of a realistic mission design will relate to the scientific problems.

### 5.1 Measuring the Variable Ocean Circulation

Altimeter measurements of variable geostrophic currents do not depend critically on an accurate geoid. Thus these currents are more easily measured than the mean currents which depend on a partition of the observed topography into a component due to the geoid and a component due to a mean current. If the ground track of the altimeter exactly repeats, then any difference in repeated altimetric measurements must be ascribed to changes in oceanic currents, apart from residual errors of measurement. However, a geoid may still be required for determination of the variability of currents over large distances, because this determination depends upon an accurate knowledge of the radial component of the orbit, and this in turn assumes knowledge of the gravity field at satellite altitudes. In the following discussion, we will consider first the problem of measuring time-variable flows, and will defer until the next section the problem of measuring mean (time-averaged) flows.

#### 5.1.1 Sampling Considerations

Schemes to adequately sample the spatial and temporal variability of ocean surface currents require the consideration of a number of factors. A frequency spectrum which is proportional to  $s^{-2}$  ( $s$  is frequency) or steeper (and this roughly describes the velocity spectrum of the ocean at periods shorter than the mesoscale) can be aliased almost with impunity simply because the aliased energy that is folded into lower frequencies is such a small fraction of the energy resident at low frequencies. A complete calculation is given in Wunsch (1972). Thus to quantify the *mid-ocean* temporal variability of the mesoscale, temporal coverage as slow as every 25 days at a given location could be tolerated.

The temporal variability in regions of strong boundary currents, as noted above, is somewhat different from that in the open sea. It tends to have shortened periods (Schmitz, 1978) and often considerably intensified energy levels. A dominant time period in the near vicinity of the Gulf Stream south of Cape Cod is 50 rather than 100-150 days. The Drake passage (Nowlin and Pillsbury, 1981) is also a region of strong,

shortened periodicity. One of the fundamental problems of physical oceanography today is understanding the interaction, dynamical and kinematical, between the mean western boundary currents (Gulf Stream, Kuroshio, Agulhas Current, etc.) and their time dependent components (meanders, eddies, rings). The sampling strategy required for these important regions is somewhat different from that for the open sea.

Within the Florida Current there are strong baroclinic motions with periods more nearly characteristic of continental-shelf waves of order 3-20 days. These periods in turn are also characteristic of the high-frequency variability of the equatorial regions.

It is not possible for a single spacecraft to cover completely the full spectrum of variability everywhere in the world ocean. To sample adequately the special regions of three-day variability would require ground tracks which repeated every 1.5 days or sooner, and this would reduce the available geographical coverage by a large factor. That is, temporal repeatability must be traded against the density of subsatellite tracks. We believe that a reasonable compromise is a basic ten-day sampling strategy. This interval provides a Nyquist frequency of one cycle per twenty days which ought to be adequate for more than 90% of the global ocean, and a track separation of 316 km at the equator (see figure 5.1). Thus this ten-day repeat time is a compromise between competing needs. But as a practical matter, the period of repetition is easily changed after launch, say from ten days to five or three days, if necessary. We can defer until later considerations of an ideal mixture of sampling rates at different phases of the experiment. For the present, we will assume a frozen orbit repeating every ten days.

The coverage implies that the altimeter will be used to map the variability field in spectral terms rather than in physical space. As can be seen from figure 5.1, only features larger than the basic size of the "diamond" pattern would be contourable. Scales smaller than this will be well determined in the long-track directions down to a spatial scale of the order of the system resolution (basically the footprint size) of about 10 km.

For purposes of studying the variability, it is often said that a good geoid is unnecessary. This is only true if the ground tracks repeat sufficiently exactly that subtraction of successive altimetric measurements removes the geoid. If successive tracks are in fact offset, then the geoid will have changed, thus introducing a spurious signal into the residual. But even with improved geoids, it will be necessary to have the ground tracks that repeat as precisely as possible, because it is highly desirable to study mesoscale variability, *i.e.*, on scales approaching the Rossby radius of deformation where the geoid can only be obtained by ships. The inevitable slight shifting that will take place over short distances means that steep spatial gradients in the geoid will appear as variable velocities.

Exact repetition can never be achieved. The degree to which near-repetition can be obtained depends upon knowledge of the actual orbit and the accuracy with which the spacecraft can be controlled. A repetition accuracy of one kilometer appears feasible, and a considerably greater error can be tolerated, although as it grows the accuracy of the variability measurement will degrade in regions of strong geoid gradients. Some strategies for dealing with improvements in these regions are required. For example, by modifying the orbit to acquire a dense coverage of ground tracks in the immediate vicinity of the nominal frozen track, it may be possible to separate the geoid contribution from the oceanic-variability contribution.

### 5.1.2 Coverage

Apart from the ice-covered Arctic Sea, the highest latitudes of extensive ocean are at about the rim of the Antarctic Continent and of the Norwegian Sea. To cover the Southern Ocean fully requires an orbit with an inclination of about 70°. At the same time, gradients of elevation should be computable with nearly isotropic accuracy at all

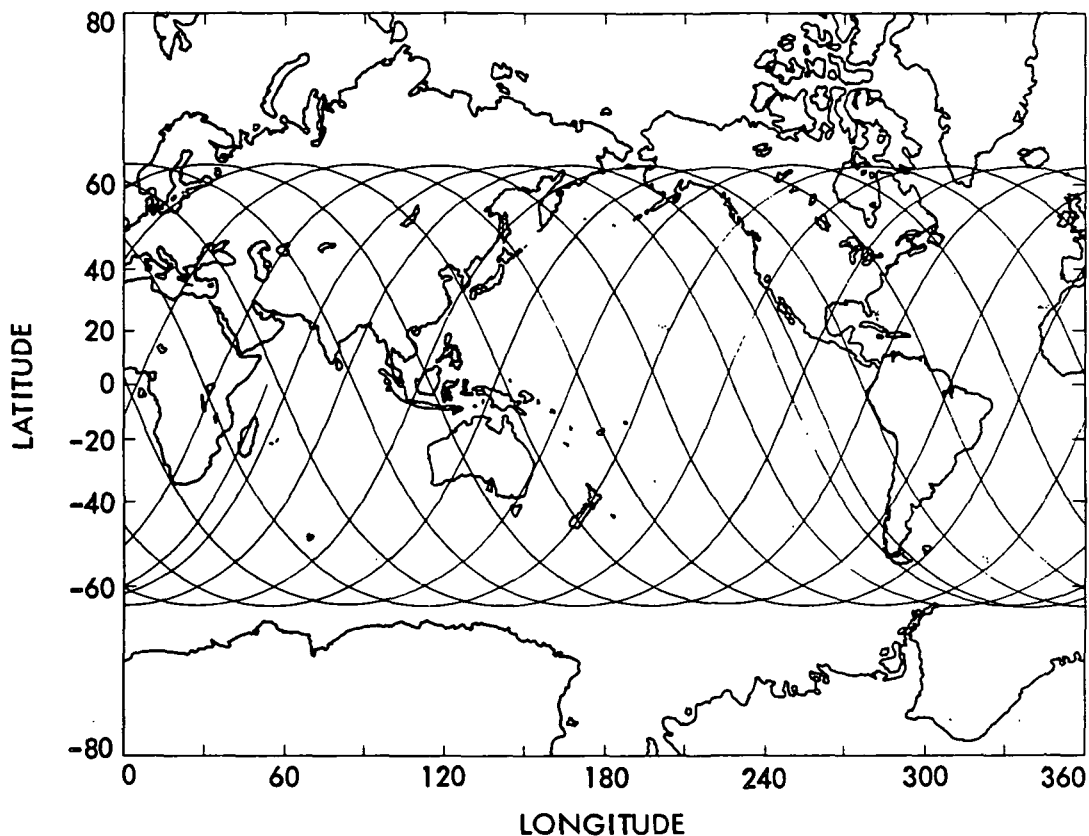


Figure 5.1 The ground track traced out by a satellite at an altitude of 1300 km and with an orbital inclination of  $64^\circ$  during a one-day period of an exactly repeating ten-day cycle.

latitudes. This requires a satellite in a low-inclination orbit in order to provide subsatellite tracks that cross at high angles.

At the present time, the best compromise seems to be an inclination of about  $65^\circ$ . As shown in figures 5.1-5.4 such an orbit sacrifices coverage of the entire Norwegian Sea as well as portions of the Southern Ocean. But we believe that this is the optimum choice for several reasons. First, as discussed below, a ten-day repeat orbit at this inclination aliases the principal tidal components into acceptable frequencies. The crossing angles of ascending and descending orbits are about  $45^\circ$  at  $30^\circ$  latitude, and the entrances and exits to the Norwegian Sea are adequately covered. But we have also anticipated the probable existence of at least one other altimetric satellite in a high inclination orbit (such as that proposed for Noss). Such an altimeter would provide nearly meridional coverage of the high-latitude oceans, which particularly for the circumpolar region, is just what is needed. By combining the two grids of observations, and by using the accurate TOPEX orbit to "calibrate" the measurements made by the other satellite, it will be possible to obtain dense coverage of oceanic variability as well as accurate observations of the polar ice fields (see appendix C.3 for the desirability of the latter).

### 5.1.3 Accuracies

The question of the required accuracy of an altimetric system is a complex one because it is a function of space and time scale as well as of region and must ultimately be determined by what is asked of the data. A few guideposts are available.

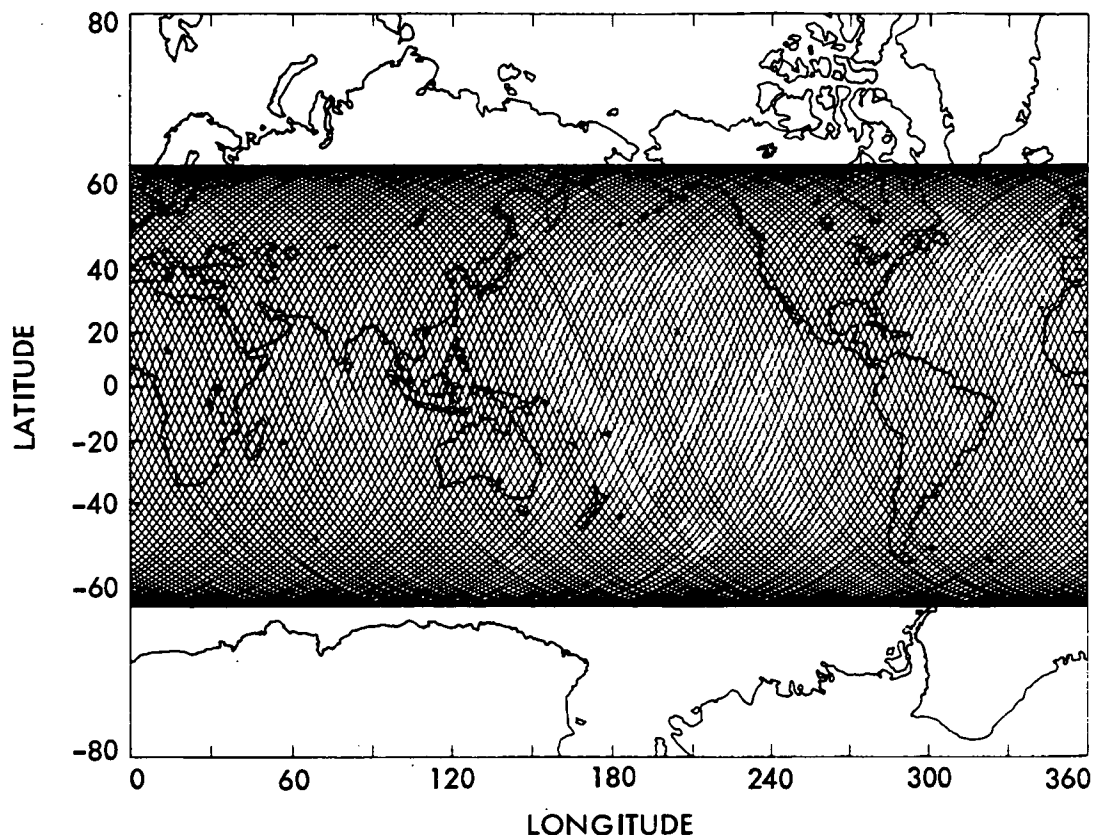


Figure 5.2 The ground track traced out by a satellite at an altitude of 1300 km and with an orbital inclination of  $64^\circ$  during a ten-day period of an exactly repeating ten-day cycle.

The variability in the immediate vicinity of the strong western boundary currents contains meanders and "rings" with elevation signatures of nearly one meter over distances of several hundred kilometers. These disturbances have been seen even with the comparatively crude Geos-3 system and very clearly with Seasat (Cheney and Marsh, 1981). To map and track the gross properties of this form of variability at a 5% level suggests a system with a five-centimeter precision over distances of order 50 to 500 km. This was evidently achieved by Seasat.

Seasonal and interannual fluctuations of the ocean circulation must be determined on the complete range of spatial scales. One of the few firm numbers available is that the range of seasonal variability of the total transport through the Florida Straits by the Gulf Stream is  $\approx 8 \times 10^6 \text{ m}^3/\text{s}$  (Niiler and Richardson, 1973) which corresponds to a change in head across the 100 km of the Florida Straits of about twelve centimeters. In other regions, the variability is considerably less, being on order five to ten centimeters (figure 5.5).

How accurately could a ten-centimeter change be determined? Assume, following the Seasat results, that in any particular pass *differences* of ten centimeters could be determined over distances of order 100-1000 km. Then in six months, with ten-day repeat orbits, the error would be  $\pm 10/\sqrt{18} = \pm 2.4 \text{ cm}$  in each track. With a nominal five-year mission lifetime, another factor of  $1/\sqrt{10}$  could be obtained, and determination of interannual differences of the annual cycle would become possible—even if the numbers quoted here should turn out to be somewhat optimistic.

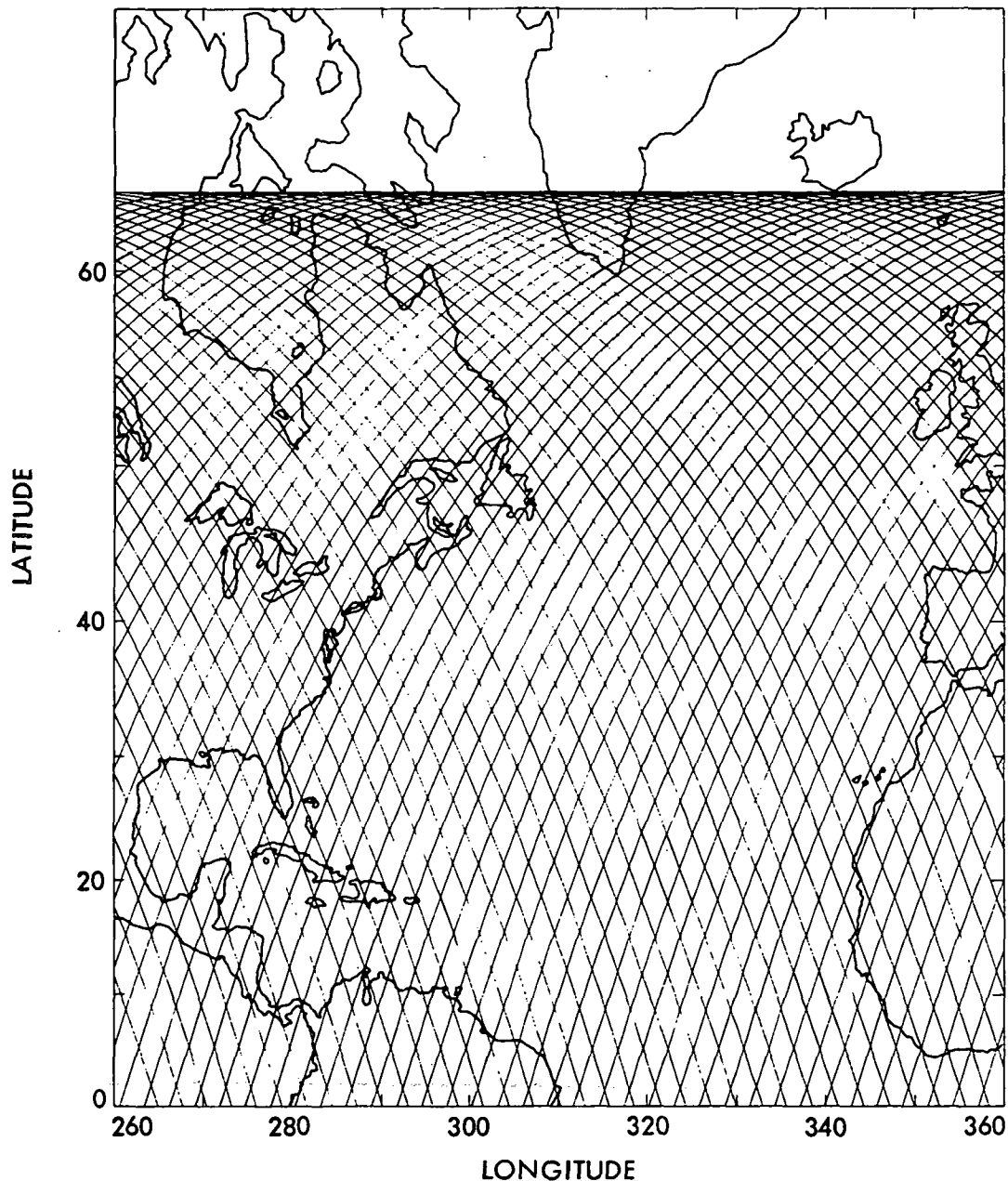


Figure 5.3 An expansion of the information shown in figure 5.2 for the North Atlantic, showing the maximum density of the satellite ground tracks obtainable over a ten-day period of an exactly repeating ten-day cycle.

But these numbers are based upon the assumption that each pass is treated independently of any other one. In practice, the passes will be used to form a *surface* computed by a so-called crossing-arc analysis. The ascending and descending tracks cross each other at a series of nodes; the difference in elevation between the elevation measured on the crossing arcs at these nodes is minimized in a least squares sense (see Rapp, 1978; Marsh *et al*, 1980 for examples of the procedure using the Geos-3 data). Based upon the experience with Geos and Seasat, the accuracy with which the slope of the surface can be found should be significantly better than the accuracy of the slope computed from any single path. Although a complete simulation has not been

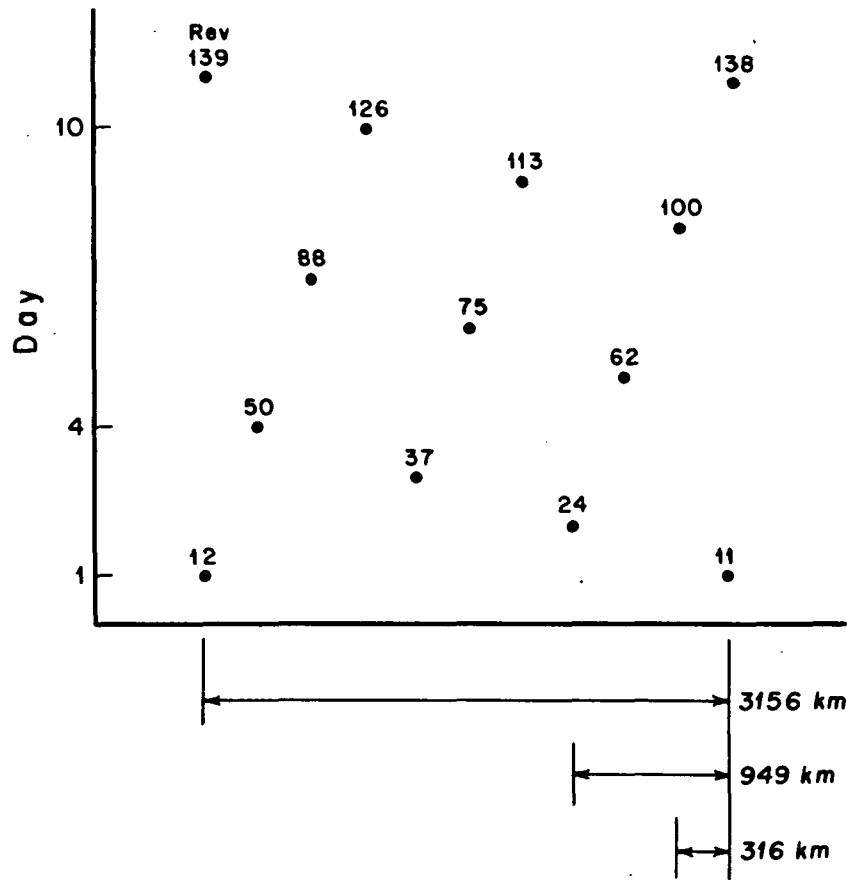


Figure 5.4 The equatorial positions of ascending ground tracks on each day of the exactly repeating ten-day cycle.

performed, the error should decline roughly like  $1/\sqrt{N}$  where  $N$  is the number of arcs in the surface. Thus in any ten-day period, figure 5.3 indicates that it should be possible to fit a locally plane surface to selected subregions of the North Atlantic containing perhaps 25 arcs. This would multiply the standard deviation of the error in the slopes by a factor of about 1/5, and give a difference error of order  $\pm 0.5$  cm in ten days.

If the mass flux through the Gulf Stream fluctuates by 10%, there must be an equivalent change in the southward return flow because the Atlantic is almost completely blocked to the north. At  $24^\circ\text{N}$ , this changed return flow must show up somewhere between the Bahamas and West Africa. Thus if the altimeter measures an increased mass flux in the Florida Straits, equivalent changes in head must occur in the open Atlantic. This is a specific example of the scale connections described above. On the other hand, it is important to know where and how the return flow occurs. For example, computations of the associated meridional heat flux (e.g., Bryden and Hall, 1980; Roemmich, 1981b; Wunsch, 1980) across the Atlantic at that latitude require a localization so that the temperature of the returning flow can be computed.

From equation 7 the geostrophic relationship, for barotropic flows, yields transport changes of

$$V = vLD = \frac{g}{f} (\Delta\zeta) D$$

where  $D$  is the water depth, independent of the horizontal distance  $L$  over which the flow occurs. Should the average water depth of the returning flow be circa 500 m, as it



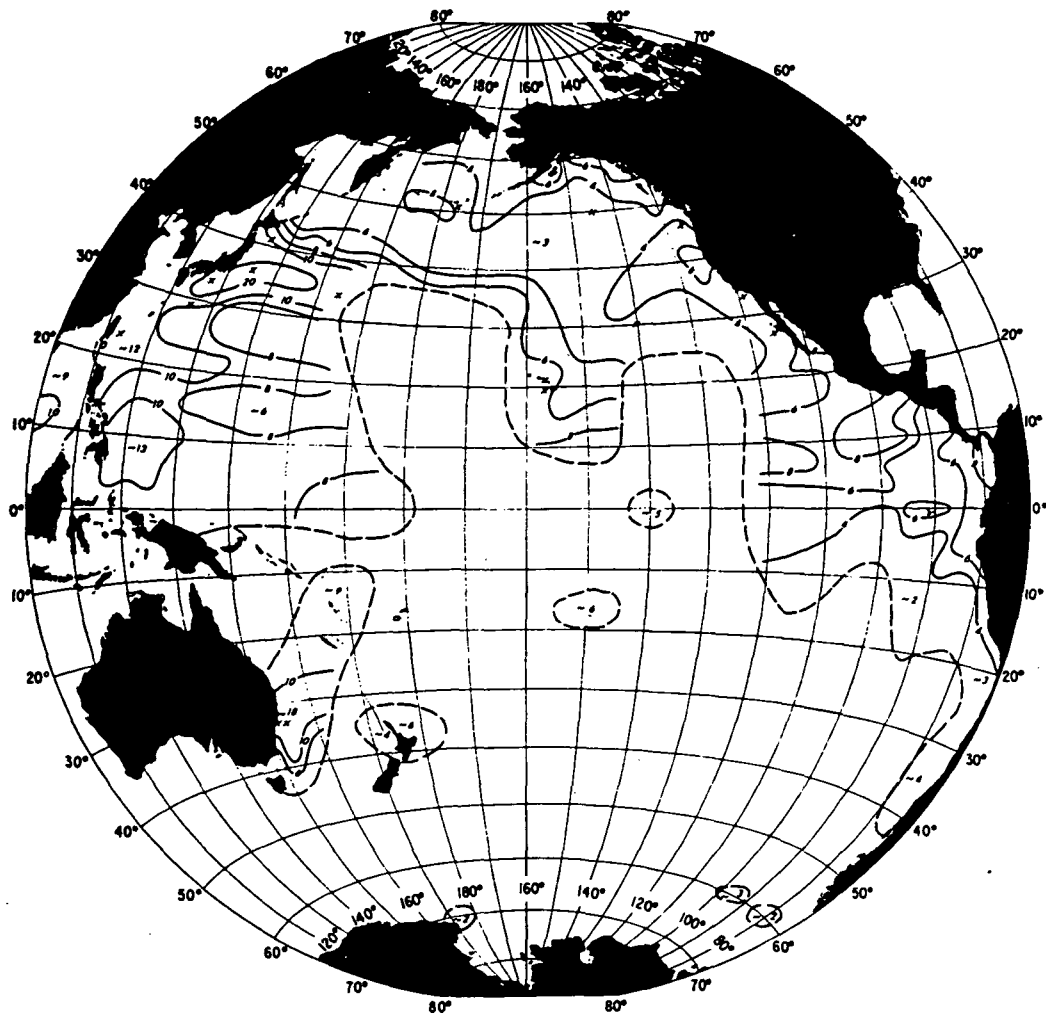


Figure 5.5 Standard deviation of dynamic height (dyn-cm) of the sea surface relative to 500 db, computed irrespective of season for each  $2^\circ$  square having at least ten observations. This figure is closely related to the standard deviation of the fields shown in figure 2.2 although somewhat smaller (from Wyrki, 1975).

is in the Florida Straits, then such a change in transport could be measured with the same averaging procedure as already noted for that region. The return flow would thus occur in a comparatively narrow jet attached to the eastern or western boundary (the only places in the section at  $24^\circ\text{N}$ , where the water is this shallow). On the other hand, perhaps the return flow is spread more or less uniformly across the section in a mean water depth of about 4000 m. (*This is a very pessimistic assumption because the warm northward-moving Gulf Stream water is expected to return to a great extent as only slightly-less-warm southward-moving water in the upper layers—and such a flow would have much larger surface velocities than are assumed here. A major problem is to deduce the depth dependence of the return flow—a question that will be ignored for the moment.*) The change in head required to return the flow is then about 0.5 cm. Could this be observed?

For the purposes of discussion the question can be reduced to asking whether it is possible to deduce a slope change of 0.5 cm across an ocean width of 3000 km?

The estimates made of the accuracy obtainable from a crossing-arc analysis suggest that such a fluctuation should indeed be determinable on periods as short as a few weeks assuming that the standard error in the precision of the system is ten centimeters or less. Any improvements in the system noise would make the determinations more robust and would be useful.

#### 5.1.4 The Fluctuating Wind Field

At least part of the fluctuations in the ocean circulation are due to fluctuations in the wind field and its curl. A key problem in oceanography is to understand just how much, and through what physical pathways, changes in the ocean are induced. The traditional observations of surface winds are inadequate for this problem, and global observations made from space are required. We expect that the scatterometer flown on Seasat (Johnson *et al*, 1980; Bracalente *et al*, 1980) will be improved and flown on future missions such as Noss. (Many of the sampling problems which render the Noss altimeter comparatively useless for studying the ocean circulation do not apply to the scatterometer measurements; *e.g.*, the aliasing of diurnal components of the wind field into long periods should be comparatively insignificant except in the immediate vicinity of land.) Preliminary analyses of the Seasat data (*e.g.*, Estoque and Fernandez-Partagas, 1980) suggest that the wind field observed by such instruments would vastly improve existing knowledge of the wind field over the oceans. It is thus extremely desirable that any altimetric mission for studying the ocean circulation occur contemporaneously with scatterometer measurements in order to permit these important studies of the relationship between the fluctuating wind field and the fluctuating ocean circulation.

### 5.2 Measuring the Mean Ocean Circulation

The ocean probably fluctuates on all time scales. For present purposes, and to avoid semantic difficulties, we will refer to the mean circulation as that given by any five-year time average. As described above, it is believed that this circulation contains all spatial scales from the Rossby radius of deformation—circa 30 km—to the dimensions of the Pacific Ocean. A determination of the corresponding time-averaged geostrophic velocity field is more difficult than that of the time-variable part because the marine geoid must be known with high accuracy even with perfect ground-track repetition. The great variety of spatial scales of significance means that no single method of determining the geoid is able to produce a geoid with the same accuracy as the altimeter. On the other hand, the circulation is a turbulent fluid, in which the different spatial scales of flow are coupled together, both kinematically and dynamically. This means that the determination of one range of scales of flow by direct means can strongly constrain flows on other scales which are not directly observed.

As an example, consider the Gulf Stream, whose width is approximately 100 km. Any fluid progressing northward in the Stream must ultimately return southward to conserve mass. The return flow is thought to contain scales from 100 to 3000 km. Total flows returning fluid southward cannot carry more fluid than the amount going northward. Thus this provides a useful constraint on the possibly unobserved larger scales. (This same argument was applied above to the time-variable part of the flow.)

#### 5.2.1 Accuracies, Resolution and Coverage

Present uncertainties in the time-averaged general circulation translate into elevation variations of up to 25 cm in some areas of strong flows and are probably in the neighborhood of 10 cm or less over more quiescent regions of the interior oceans (see figure 5.5; Wunsch, 1981a; and Stommel, Niiler and Anati, 1978). The simple statistical arguments used for the variability also suggest that accuracies of this order can be attained in the altimetric system with comparably short averaging times, on all the spatial scales of relevance. But, for the time averages, particularly over the longer

distances, it is the systematic errors that will dominate, not the random errors. (For the variability, the systematic errors will tend to cancel by subtraction.) The TOPEX Precision Orbit Determination Group (1980) has concluded that the residual systematic error should be no greater than about five centimeters in any particular orbit assuming that the Gravsat mission is flown. This value, which may actually be high, is the sum of the residual gravity-field uncertainties plus systematic uncertainties in the influence of radiation pressure. The five-centimeter level is well below the existing level of uncertainty in the sea-surface elevation (Wunsch, 1981b).

Because of the scale coupling in the ocean, it is not possible to make completely unequivocal requirements of accuracy and resolution. The major difficulty in designing an altimetric mission for studying the general circulation lies in the geoid problem. Suppose that a geoid is constructed (by a specialized gravity mission, by shipborne data, by orbital analysis), and that it represents an average over  $x_0$  kilometers. Suppose further that it has an error variance of  $\epsilon^2 \text{ cm}^2$  and that the spectrum of this error is roughly  $A k^{-2}$  (i.e., vanishing at the longest wavelengths where orbital geoids are very accurate, and having its greatest error at the basic averaging interval, i.e.,  $k_0 = 2\pi/x_0$ ), where the constant  $A$  is determined by

$$\int_0^{k_0} A k^2 dk = \epsilon^2$$

Assume also that the spectrum of the true geoid is nearly  $B k^{-3}$ . (These assumptions describe a geoid with the most energetic components having the smallest error, a description that perhaps is not entirely true). Thus assuming very accurate altimetry is obtained from a multi-year average, the error introduced into surface geostrophic velocities, and thus into water transports, by the geoid will clearly be minimal on the very longest spatial scales and will grow (like  $k^5$  in spectrum) with shorter scales. Assume that there is a wavenumber  $k_c$  where the error in the surface geostrophic velocity becomes so large that it is not useful. This results in a statement that the surface geostrophic velocity and hence water transport is known in a low wavenumber bandpass  $0 < k < k_c$ . Is this useful, and how does it depend upon  $k_c$ ?

The geoid discussion (section 4.1.1) suggests that with a special purpose Gravsat mission,  $k_c = 2\pi/200 \text{ km}$  globally, with an error in elevation of 1.5 cm, corresponding to surface velocity errors of 2 cm/s. The cutoff  $k_c$  can be increased regionally, at this level of error, by shipborne gravity measurements. If  $k_c$  is decreased to  $2\pi/500 \text{ km}$ , the surface velocity error is considerably less than 1 cm/s. The question of the usefulness of this result must be answered quantitatively in the context of what is known now about the oceanic general circulation. A formalism for doing this has been constructed by Wunsch and Gaposchkin (1980) and used in a preliminary study by Roemmich (1981a). The density field of the ocean alone, to the extent that it is known and representative of the long-term average values, implies—through known dynamics—certain constraints upon the surface geostrophic flows (see Davis, 1978). Altimetry provides information that can be either independent or redundant in terms of what is already known. Preliminary tests (Roemmich, 1981a) suggest that realistic estimates of the type of information that is likely to be available from altimetry and a gravity mission (i.e., one that will have determinations of the weighted average of surface geostrophic currents with an accuracy of 1 cm/s where the interval of averaging is 500 km or less) will be largely independent of existing knowledge and this would greatly advance knowledge of the general circulation.

### 5.2.2 The Wind Field

To the extent that winds are also available (presuming again that they will be measured by a spaceborne scatterometer such as that proposed for Noss), it will be possible for the first time to study the specific relationship between observed mean-flow fields and the mean stress that drives them. Such studies are now extremely rare, given the paucity of both reliable wind observations and ocean-circulation measurements. Almost for the first time, it will become possible to actually test existing dynamical hypotheses of the linkages between the ocean circulation and the wind stress (curl). This would constitute a nearly revolutionary advance in our understanding of the general circulation of the ocean.

### 5.2.3 Duration

Many of the direct observations made over the past decade (e.g., The Mode Group, 1978) suggest that long-term averages are required to find the mean flows in the presence of strong variability—typically over two or more years in many locations. A mission lifetime of about five years represents a reasonable compromise between the need to have very long averages for stable statistics of both the mean and variable currents and the increased costs of long missions. A five-year mission will permit a five-year averaging interval that is longer than most extant *in situ* observations, good determinations of the annual cycle (which are of very great interest both dynamically and climatologically), good first determinations of the interannual variability of the seasonal cycle from year to year, and highly stable statistics of the shorter-than-annual variability. Cartwright (1980) has shown that the five-year lifetime will permit a determination of tides from the altimeter data, a determination which will vastly improve our knowledge of global tides, and which will remove the tides as sources of significant error in the determination of the ocean circulation.

## 5.3 The Ocean at Depth

An altimeter observes only surface geostrophic pressure (velocity) fluctuations. Optimal use of such information requires ways to couple it with other information about the ocean's interior. Because direct determination of the ocean's interior density, mass, and velocity fields from satellites does not seem possible, we envision obtaining such knowledge in at least two distinct ways: (a) from models of ocean dynamics using the surface observations as boundary conditions, or (b) from direct observations made by *in situ* instruments.

### 5.3.1 Inference from Models

Ocean dynamics as currently understood can be used to model the interior ocean with the surface field as boundary conditions. The governing equations for quasi-geostrophic variability, for example, can be expressed as sums of vertical normal modes. The great bulk of the mesoscale variability manifests itself in density as simple vertical movement of the thermocline, although there are quantitative complexities in any given region. Thus, models can be used to explore the implications for the interior ocean of changes at the surface. Undoubtedly there would be regional tests, with *in situ* measurements of the different parameters used in the models.

Consider first the variability. Recent mesoscale-variability experiments have suggested that the velocity in the interior of the ocean tends to change, at least in the band of periods from weeks to months, essentially as the sum of two "modes": (a) the barotropic mode which leaves the mass field unchanged and which has a velocity profile that is independent of depth; and (b) the first baroclinic mode which moves the thermocline up and down and which has a horizontal-velocity profile with one zero crossing at depth (typically at about 1200 meters). In regions where these two modes have different characteristic horizontal wavenumbers, a best fit to the observed changes in

surface velocity (or pressure) can be made, thus determining the changes in density and velocity with depth (these are computed relative to the time averages). Such ideas can be elaborated to account for such variables as bottom topography and mean shears, and will have an accuracy directly dependent upon the reliability of assumed models.

For the time-averaged flow, as with the variability, measurements of the surface pressure fields must be translated into useful information about the subsurface fields. Again there are two strategies possible. In many existing studies of the time-averaged circulation (which do not yet properly account for time-averaged circulations driven by fluctuating flows) the governing equations can be reduced to a single, nonlinear, partial differential equation (e.g., Needler, 1967; Veronis, 1969; Welander, 1971) of fourth order in the vertical coordinate. Specification of the surface-pressure field alone, along with bottom-boundary conditions of no normal flow of momentum or heat, are inadequate by themselves to determine the full solution. On the other hand, the success of the known analytic similarity solutions, which have a comparatively simple structure in the vertical, suggests that simple parametric solutions may be determinable from the surface pressure field. But the existence of estimates of wind stress from scatterometers, and hence of the derived curl and Ekman divergence, provides what is at least formally the missing upper boundary condition. At the present time, it is not known to what extent the surface pressure fields and Ekman divergence which contain inevitable measurement errors will allow deduction of the interior density field. This is a problem for further investigation. However, we note that altimetry plus scatterometer measurements differ from all other possible measurements from space in that *at least in principle they directly measure the boundary conditions of the dynamical equations governing the three-dimensional movement of the fluid*. In the atmosphere, specification of the surface fields alone does not provide adequate information for computing the fields at higher elevations; but the ocean differs significantly from the atmosphere in having all of its energy sources at the surface (there is no oceanic analog of radiation absorption at high altitudes).

### 5.3.2 Inference from Subsurface Observations

The second strategy for obtaining fields at depth is of course the direct use of *in situ* observations such as ships, floats, drifters, and moorings. These platforms are mismatched to the sampling capabilities of satellites. Nonetheless, because the long wavenumbers in the oceanic circulation seem to correspond to small frequencies in the variability, ships can be used for studying the time-averaged circulation. The picture of the circulation now available in fact has really been built up by treating decades of observation as though made simultaneously. In section 6.7, there is some discussion of a global ship and *in situ* observational strategy that might be implemented by the international community if an altimetric mission were to be flown. Another promising remote-sensing technique (but not a spaceborne one) is the use of acoustics in the form of tomography as described by Munk and Wunsch (1979). This technique may be economically feasible because of the geometric growth in information content with numbers of moorings. A combination of basin-wide acoustic tomography plus altimetry would provide the complete three-dimensional time-variable velocity, density, and pressure fields.

We believe that a realistic strategy involves a combination of *in situ* measurements with the type of direct dynamical modelling envisioned above.

## **6. AN OCEAN TOPOGRAPHY EXPERIMENT (TOPEX): A PROGRAM**

Knowing that the shape of the sea surface, its topography, carries information about surface currents, tides and waves, and knowing that the topography can be measured by satellite, we can design a specific experiment to study the general circulation of the ocean using a satellite-borne altimeter.

### **6.1 Primary Goals**

The primary goal of the experiment is to measure the surface topography of the ocean (the ocean surface pressure) over entire ocean basins for several years, to integrate these measurements with subsurface measurements and models of the ocean's density field in order to determine the general circulation of the ocean and its variability, then to use this information to understand the nature of dynamics, to calculate the heat transported by the oceans, the interaction of currents with waves and sea-ice, and to test the ability to predict circulation from the forcing by winds. An important benefit would be a greatly enhanced estimate of the geoid permitting a great variety of geophysical studies which are impossible now. This is an ambitious program that blends space and conventional measurements into a program for the study of ocean circulation and geophysics. As such, it will require not only a carefully thought out satellite system, but also the cooperation of important segments of the international oceanographic community. In return, the program promises to provide a global view of ocean dynamics, a view that has thus far eluded oceanographers, and to provide information of fundamental usefulness to oceanography, weather prediction, climate and fisheries.

This primary goal can be approached in a series of steps, each of which produces important and useful information, but each of which is a clearly defined task.

### **6.2 Secondary Goals**

In addition to the primary goal of studying the oceanic circulation using altimeter observations from satellites with a well-determined orbit, other useful observations can be made by spaceborne altimetric systems. These are discussed in appendix C, and are only summarized here.

Altimetric studies of the height of the sea surface in coastal regions, when combined with measurements of wind and wave height, will make major contributions to the solution of long-standing problems in coastal oceanography. Each year storm surges damage coastal areas and kill people, yet an understanding of the dynamics of surges requires observations of surface elevation, winds, and waves during storms in shallow coastal areas, observations that are difficult to make by conventional means, but which with luck could be made by TOPEX (storm surges are rare enough that they tend not to coincide with satellite observations). In addition, shallow seas are the major absorbers of tidal energy, and observations of tidal heights in regions such as the

Patagonian Shelf and the Bering Sea will provide substantially better estimates of tidal dissipation than are now available. Topex could also contribute to knowledge of frozen areas. Altimeter observations from TOPEX, when combined with similar observations from Noss will allow the latter to profile the glaciers of Greenland and Antarctica with accuracy sufficient to determine whether these ice sheets are growing, contracting, or likely to surge, questions of fundamental importance to glaciology and the study of climate. Lastly, it may be possible to modify the altimeter to allow it to observe scatter from rain immediately above the sea surface. At present, little is known about oceanic rainfall, and such measurements, when coupled with radiometric observations of liquid water in the atmosphere (also made by the satellite), will contribute to our understanding of the role of rain in weather and climate.

### 6.3 The Mission

The proposed altimetric mission (called TOPEX) has the following nominal characteristics, stated together with a brief recapitulation of their rationale:

(a) A dual-frequency altimeter to measure the height of the satellite independently of the electrons in the ionosphere. As a by-product this will provide global measurements of that quantity.

(b) A nonscanning radiometer to correct for the influence of water vapor on the altimeter measurement.

(c) An orbit with an altitude of 1300 km and an inclination of 65°. This altitude is high enough to minimize the effect of atmospheric drag, and to slightly reduce the influence of errors in the earth's gravity field, although radiation forces will be slightly larger. The inclination provides high crossing angles between ascending and descending tracks at mid-latitudes, while providing good coverage of the world's oceans.

(d) The basic mode of operation is a 10-day frozen orbit but the mission will retain the ability to modify the ground track coverage from time to time for special purposes. This sampling interval should provide adequate temporal coverage of the great bulk of the ocean surface. Repeat orbits are desirable because they greatly simplify the data analysis and make it possible to study oceanic variability even at spacial scales where the geoid is inadequate.

(e) A precise determination of the satellite orbit through a combination of dynamical models of the satellite and precision tracking. The tracking may be done using either laser or radio methods; but we strongly recommended that the all-weather capability of radio techniques be explored as a feasible method. Without precise orbits, we cannot make useful oceanic measurements.

(f) A complete, documented, data-handling system, in place no later than six months before the launch of the satellite. Data must be analyzed in a timely manner and without long delays once the first data become available after launch.

(g) A comprehensive program to evaluate and apply the data produced by the experiment in order to fully exploit the information content of the TOPEX data.

(h) The minimum mission lifetime is five years, even if this requires a ready-to-fly backup spacecraft. This lifetime will provide a minimum period over which reasonably reliable average current fields will be computable (an estimate based upon the available *in situ* measurements) and because it will provide a first quantitative examination of the annual cycle over five realizations permitting at least a qualitative examination of the interannual variability and the variability in the annual cycle itself.

The nominal mission makes two major assumptions which, if they should turn out to be incorrect, would require a reevaluation of the mission:

(a) *We assume the eventual existence of a dedicated satellite for determining Earth's gravity field (Gravsat).* The Science Working Group has concluded that the

determination of both the time-variable and the time-averaged components of the ocean circulation are of equal importance, and that the significance of TOPEX to oceanography is vastly increased with a serious attempt to do both. In any event, the argument that the time-variable circulation is more easily achieved than the time-independent part, because of the absence of a need for the Gravsat mission in addition to TOPEX, is somewhat misleading. While it is true that on the shorter spatial scales, (order 100 km) a high precision geoid is unnecessary if the satellite is in an exactly repeating orbit, the longer-wavelength components of the variability can only be obtained if the orbit is well known on these wavelengths. The conclusion of the Precision Orbit Determination Team is that improvements of the geopotential as would be obtained from Gravsat are a necessary component of the process of determining the orbit to the requisite accuracies. Furthermore, elimination of the geoid from the calculation of the variability requires that the ground tracks repeat with an accuracy of about one kilometer, an accuracy which we believe TOPEX can achieve. It is highly desirable, but not absolutely essential, that the six-month Gravsat mission be flown prior to the end of the five-year lifetime of TOPEX.

In the absence of Gravsat, TOPEX will focus primarily on the variability of the general circulation, itself an important scientific problem. Inferences about the absolute, time-averaged currents will then be made through more familiar techniques, *i.e.* by combining TOPEX data with *in situ* observations and models. The Science Working Group notes that improvements in the determination of gravity field can be introduced retrospectively into the altimetric data sets at any time. In addition, greater emphasis would be placed upon obtaining by ship regional surveys of the gravity field for use with the altimeter data. This will be time consuming and expensive, and will never yield global coverage. Nevertheless, many of the goals of the mission would still be achievable on a regional basis.

(b) *We assume the existence in simultaneous orbit of a spacecraft capable of measuring oceanic wind velocity.* We rely upon a scatterometer such as that proposed for Noss to supply the wind-field measurements. Should no scatterometer data be available the Science Working Group would reopen the question of whether TOPEX should carry its own scatterometer. In the absence of scatterometer observations, the use of the altimetric data will have to rely upon conventional sources for determining wind forcing at the sea surface. These sources consist of merchant ships and observations of cloud motion made by geosynchronous satellites. Although not as accurate nor as global in extent as the scatterometer observations, these sources would still permit many of the goals of the mission to be met.

Note that this nominal mission is close to that determined by Cartwright (1980) as near-optimum for tide observation. (Appendix B provides a considerably more detailed statement of the design tradeoffs of orbit-parameter manipulation.) The system described would be capable of single-orbit accuracies with a  $\pm 10$  cm or less standard error over distances of 3000 km, assuming the error spectrum is white from 3000 to 30 km.

Such a mission would determine the global field of variability as it manifests itself at the sea surface from time periods of 20 days to 5 years on spatial scales of 30 km to the width of the ocean basins. When combined with shipborne observations and models of the field of flow at depth, it would provide estimates of the general circulation of the ocean averaged over five years. It would also permit studies of the relationship between the global mean wind and the mean flow fields, and between the variable winds and the variable flow fields.

As a consequence of these capabilities, there would be a host of separate, important problems which would also become accessible to solution. Some special problems are described briefly in appendix A. Here we will mention only a few other examples:



(a) A determination of the meridional heat flux of the ocean, its variability, and, potentially, a much increased understanding of its climatic consequences.

(b) Determination of the variability and mean properties of strong current systems, fronts, upwelling regions and other areas with potential applications to fisheries, military problems, and ship routing.

(c) Indirectly, much stronger constraints upon water-mass conversion rates in the ocean, with impact upon such questions as the rate of CO<sub>2</sub> and heat uptake in the deep sea.

(d) Observations of tides, particularly in shallow seas, useful for determining tidal dissipation and for producing accurate models of oceanic tides of importance to other geophysical investigations and for prediction of coastal tides and tidal currents.

(e) Observations of waves in the vicinity of strong currents with an accuracy ( $\pm 10\%$ ) suitable for examining the interaction of waves and currents.

#### **6.4 Experimental Program**

The realization of these goals requires coordinated programs in oceanography, marine geodesy and orbit determination. The work will be difficult, involving a reduction by an order of magnitude in present inaccuracies of the observation of sea-surface topography from space. However, these goals are realistic in that we expect substantial improvements in knowledge of the geoid and in the ability to determine orbits, the two major contributions to inaccuracy. Nevertheless, the experiment must be planned in ways to optimize the accuracy of the measurements. This requires a program to improve knowledge of Earth's gravity and the geoid, technical developments to improve the accuracy of orbit determination, studies of present sets of data to understand optimum ways to conduct future work, careful calibrations of the satellite system for observing topography and the integration of space, surface and subsurface observations into oceanographic experiments.

##### **6.4.1 Orbit Determination**

The variations in the height of the satellite which carries the altimeter will be superimposed on the altimeter measurement of height. In particular, observations of the global or regional circulation using altimetric measurements are limited by the ability to determine the radial component of the satellite orbit. The accuracies associated with the best-determined contemporary geodetic satellites are summarized in table B.1. The radial orbit accuracies achieved during the Seasat mission varied with geographic region and tracking coverage, and ranged from sixty centimeters to two meters. Accuracies on the order of sixty centimeters were possible primarily because of the effort concentrated in the Seasat Precision Orbit Determination Experiment (Tapley and Born, 1980; Schutz *et al.*, 1980; Marsh and Williamson, 1980; and Colquitt *et al.*, 1980).

The inaccuracy in the determination of the radial component of the Seasat orbit is between one and two orders of magnitude greater than the five-centimeter accuracy required for the radial component of the TOPEX orbit. Such accuracies can be achieved, but accomplishing this objective will require critical study of the important factors which limit accuracy. These factors include: (a) the effects of tracking-data distribution and accuracy, (b) the influence of the spacecraft design and fabrication, (c) the inaccuracy of techniques for computing orbits, and (d) the development and refinement of models for the forces which influence the satellite motion. A discussion of the relative importance of these factors may be found in appendix B, and the principal conclusions are summarized here.

The major uncertainties in determining the satellite's orbit are due to errors in knowledge of the geopotential, drag, and the force of solar and terrestrial radiation.

The Gravsat mission can substantially reduce the former, but to reduce the effects of the latter, the experiment will require a compact satellite at altitudes near 1300km where drag is small.

At the accuracy level of a few centimeters, a number of other geodetic influences become important. These include knowledge of the tracking-station coordinates, polar motion, and Earth rotation, as well as the effects of the solid earth and ocean tides. It is anticipated that significant improvement in understanding these processes will be forthcoming from the analysis of laser ranging to the Lageos satellite under the NASA Crustal Dynamics Project.

#### **6.4.2 Calibration**

The exacting accuracy required by the experiment requires careful calibration of the satellite system. This can be done in three steps: (a) calibration of the altimeter by careful tracking by stations immediately below the satellite; (b) calibration of the ability of the satellite to measure surface currents; and (c) calibration of the ability of the satellite to survey ocean basins. The first is a direct calibration of the altimeter. The second is best done by repeatedly measuring topography along the same oceanic section, that is, by having a satellite in an orbit which exactly repeats. In this circumstance, any variation in the satellite's observations of topography must be due to noise or changes in surface velocity. Hydrographic surveys and subsurface current measurements made along the satellite track will independently determine the surface current and provide an estimate of the satellite's accuracy. The third requires repeated measurements within a region. This is best done in the Northwest Atlantic off the U.S. East Coast. There the tides, currents, geoid and atmospheric structure are well known in an area with accurate tracking. Studies conducted in this region should demonstrate the accuracies of satellite observations of the surface circulation and the accuracy of currents calculated from satellite and subsurface observations. A more general calibration process will come from the use of the altimetric data sets in the context of other, independent, oceanographic measurements. The data sets must be mutually consistent in a variety of ways. For example, the spectrum of surface variability as determined from the altimeter must agree with that determined by other methods—otherwise one or the other measurement would become suspect.

To ensure that the calibration be done to the great accuracy required by the Topographic Experiment, we recommend that a group to study the best calibration procedures should be appointed very early in the program planning.

#### **6.4.3 Data Handling and Computation**

The data streams from Earth-orbiting satellites are much larger than those normally encountered in oceanography, the algorithms for producing geophysically useful numbers are highly complex, and the data must be combined with data collected from other satellites (*e.g.*, winds and geoid) as well as with data collected from entirely different observing systems (*e.g.*, hydrographic data from ships). Investigators need to sort and merge the different data streams for different purposes—*e.g.*, to extract time series at single points, to construct regional maps at fixed times, or to regrid for comparisons.

Experience with Seasat suggests that it is essential that a complete data handling system must exist and have been tested well before the launch of TOPEX. Even though algorithms for correction may later change, the community of scientists and engineers responsible for using and evaluating the TOPEX data set must be able to understand and evaluate a complete end-to-end system before being inundated with the actual mission data. Thus a required component of any TOPEX mission is a data center with resident experts in data management and in remote sensing and with access to oceanographic experts. Such a center could be a subcomponent of a larger NASA data

center. It would be highly desirable if information in this center could be accessed remotely so that TOPEX investigators may manipulate large subsets of the data from their home institutions. Whether major segments of the complete TOPEX data sets would be transmissible over telephone lines we leave as a detail for further study. A committee should be established to study the detailed workings of the TOPEX data center, including the question of the extent to which that center will also archive the non-TOPEX data sets required to make maximum use of the TOPEX information.

In addition to providing TOPEX and other data for studying the ocean, the center must be able to make massive computations involving, for example, very large systems of simultaneous equations. We anticipate that much of the data will be used to update working numerical models of the general ocean circulation in the "assimilation" mode familiar to meteorologists. This will require a very large computational facility, and the committee should consider whether such a facility should be part of the TOPEX data handling system, or whether it should be physically separate.

We note in particular that the Ocean Data Utilization System (ODUS) study being conducted by NASA may eventually result in a center and facility that would handle the TOPEX data as part of a larger problem.

### 6.5 The Noss Program

The existence in simultaneous orbit of the Noss spacecraft is an important component of the TOPEX mission as we have outlined it here, because it will provide the extremely important wind-field measurements necessary for calculating the forced oceanic response. We thus call attention to the need to fly the spacecraft at the same time. In addition, the Noss altimeter system, which by itself is inadequate to study the ocean circulation would become very useful in the presence of TOPEX. A crossing-arc analysis of the two altimetric measurements will allow us to calibrate the Noss altimeter nearly to the accuracy of the TOPEX system. Even if useful only for geophysical purposes, this would greatly enhance the value of the Noss mission.

Because Noss does carry an altimeter, we need to briefly review the reasons it cannot by itself meet the requirements to study the circulation:

(a) The Noss spacecraft will be in sun-synchronous orbit. This means that the dominant solar tide,  $S_2$ , will be aliased into the mean topography of the sea surface. As already noted, the uncertainty over much of the ocean in the mean sea surface is less than about 10 cm. The only way that Noss could then be used to study the mean ocean circulation would be to subtract *models* of the ocean tides from the altimetric data. But this will require extraordinary accuracy in the tidal models. Nor will the satellite itself be capable of directly improving global knowledge of the solar tides. The solar tides will be split by the cycle-per-year orbital motion of the Earth about the sun. This splitting means that the very important seasonal cycle in the ocean will contain a strongly aliased tidal component which will also be very difficult to remove from the data. The sun-synchronous orbit will also alias the most prominent lunar tide,  $M_2$ , into one cycle per 14 days, thus reducing the number of these cycles in the mission lifetime and compromising the ability to determine well the global lunar tides.

(b) Noss will be in a high-inclination orbit, forcing the ground tracks to be nearly meridional. This configuration means that only the zonal components of geostrophic flow will have a chance to be determined well. The ability to construct a mean topographic sea surface as in Marsh *et al.*, (1980) depends upon the angle  $\theta$  at which the ground tracks cross each other; and the error incurred in the arc-crossing analysis depends roughly upon  $\cot \theta$ . With the high-inclination orbit, Noss ground tracks will cross at very small angles in mid latitudes, suggesting a very poor control of the error in the zonal relationship of neighboring tracks. We note in passing, that many of the most important climatological questions about the ocean, *e.g.*, the meridional heat flux, will be very poorly determined with the Noss altimeter.

(c) The Noss spacecraft will be poorly tracked in a low altitude, high drag orbit. There are two effects here. The poor tracking and high drag means that the orbits will not be well known, thus incurring a large error in the long wavelength components of surface speed. For this reason it is often said that Noss will be able to determine well only the mesoscale (order 100 km) variability. But even such a limited goal presumes that the ground tracks will repeat nearly exactly—at least sufficiently closely that the geoid, which will be poorly known on the 100-km scale, does not change significantly between tracks. But the high drag means that there will be a large and unpredictable shift between tracks, further implying that in many regions the major change will not be in the water but in the geoid. Thus even the mesoscale variability may be poorly determined in many regions. The spacecraft itself is inherently a high-drag one because of the many, very large instruments which it must carry. No feasible orbit can render it low drag.

Many of these problems disappear in the presence of TOPEX and make it possible to take advantage of the Noss altimetric data and to greatly enhance its scientific value. Briefly, TOPEX will provide a global measurement of the tides which will feed back into the tidal models used to correct the Noss data. The low inclination of the TOPEX orbit means that the TOPEX ground tracks will cross the Noss tracks at a high angle, making it possible to tie the Noss tracks together one to another and to combine the two data sets into one.

There are two ways in which the TOPEX can take advantage of the Noss satellite. The low inclination TOPEX orbit means that the high-latitude oceans, principally the Norwegian Sea and the near-pole regions of the Southern Ocean will not be covered (for any practical orbit they would not in any event be covered with high accuracy). The high-inclination orbit of Noss will cover these regions with near-meridional ground tracks. Except for the tidal aliasing problem, Noss will provide some useable coverage of the variability there. The combination of Noss and TOPEX data will also allow the Noss to accurately measure the shape of continental ice sheets in Antarctica and Greenland, a primary goal of the Ice and Climate Experiment (NASA, 1979; also see appendix C). In mid-latitudes, Noss will provide primarily a denser surface coverage for geoid determination

*Most important are the scatterometer wind measurements by Noss.* The purely solar period (diurnal component) of the wind is believed important only in the immediate vicinity of the continents (sea-breeze effects) and the aliasing by solar components is probably small. The wind measurement is vital for maximum use of altimetric data sets both for the variability and mean ocean circulation.

## 6.6 Resources

The program will require the cooperation of the oceanographic research community within this country as well as elsewhere. We recommend that NASA be responsible for providing the satellite system and for processing data from it so as to obtain surface geostrophic currents, wave height, ice boundaries, etc., and that NASA fund, through an Announcement of Opportunity, a number of scientific studies based on data from the satellite. These should address the major goals of the program and particular attention must be paid to the required modelling effort. However, we expect that other studies, and other applications of satellite data to oceanographic problems will be required. We recommend that these be funded partly by other agencies, particularly the National Science Foundation, the Office of Naval Research, and the National Oceanic and Atmospheric Administration; but NASA must retain responsibility for ensuring that a comprehensive effort is actually mounted.

## 6.7 The International Context

The proposed TOPEX mission fits naturally into current international discussions of optimum strategies for measuring the oceans over the next decade. With the end of the Global Weather Experiment much meteorological interest has begun to shift toward the second objective of the Global Atmospheric Research Program—that of understanding climate and its changes. In contrast to weather, the slow variability of the climate means that the role of the ocean cannot be regarded as secondary. For example, the question of whether the ocean really carries as much of the meridional heat flux as calculated by some meteorologists (*e.g.*, Oort and Von der Haar, 1976; Hastenrath, 1980; Trenberth, 1979) is of considerable importance in understanding global climate and its changes. Other climatologically important questions are of immediate interest to national policy. For example, we do not know the implications of the growing amount of atmospheric carbon dioxide produced by the combustion of fossil fuels because we do not know how much carbon dioxide the oceans can take up directly. Nor do we know the rate at which the ocean will warm under a warming atmosphere (see National Research Council, 1979a; Department of Energy, 1980).

These and other problems have led to national and international discussions of the usefulness of some kind of international effort in the late 1980s for deducing the large-scale circulation of the ocean. There is some urgency in the effort because the tritium in the oceans, which was mostly produced by atomic tests in the 1950s, is slowly decaying away. If the effort were postponed much beyond the present decade, this possibly unique opportunity to measure the evolution of an artificially induced passive tracer will be gone forever.

Although no details have been determined, and indeed there are neither national nor international commitments to any of the work, one can begin to see the outlines of an international effort at measuring and monitoring the ocean to which TOPEX would bring a powerful new capability and indeed which would spur efforts to take advantage of its unique view of the sea. Such an effort can be thought of as a Global Ocean Circulation Experiment; it would have many elements. A major component would be a near-global shipboard program to measure density, chemistry, and gravity. This would have several goals. It would provide a baseline census of the temperature and salinity of the ocean in the present epoch for comparison with future censuses to deduce major long-term climatological changes. It would measure the tritium and other tracer distributions for study of the large-scale property distribution of the sea. And it would provide the detailed measurements of gravity necessary to construct regional geoids. In the TOPEX context, there are two direct connections. In any given ocean basin it would provide the hydrography to accompany the TOPEX determination of the surface geostrophic flow allowing, as described above, the first direct determination of the absolute geostrophic general circulation of the ocean. In addition, because ships can only cover the world's oceans sequentially, TOPEX would provide a measure of the inter-basin variability on the annual and interannual time scales so as to permit an understanding of the representativeness of any survey of an ocean at a particular time.

In addition, we anticipate that many purely regional experiments would occur because of the availability of the TOPEX measurements. These experiments would require little international coordination but it is important that the TOPEX timetable and capabilities be widely disseminated long in advance of the actual mission because the logistics of oceanographic expeditions require considerable advance planning.

## 6.8 A Rational Chronology

We have outlined here the elements of an altimetric mission and have tried to provide some nominal requirements and solutions. Engineering studies of the details of the optimum altimeter, radiometer, orbital altitude, and inclination should continue until such time as there exists a consensus on the best approach. We believe that a

timetable leading to a launch about 1986 will provide ample time for these studies, for detailed engineering design, and for procurement and launch, as well as time for developing plans for using the altimetric data.

## **6.9 Analysis of Present Data**

Both Geos-3 and Seasat produced more-or-less accurate observations of sea-surface topography; much of this document is based upon experience with these satellites. Yet the information in these observations is not exhausted, and for Seasat the analyses are only just beginning. Further investigations are necessary in order to plan optimal scientific experiments in the future.

The major unfinished analysis combines altimeter, geoidal, orbital and subsurface observations in an inverse problem to determine simultaneously the orbit, geoid, and currents which best fit the observations. All are intimately interconnected, and all must be solved for at once. To do this requires firm estimates of the errors in each set of data and the structure of these errors. That is, each data set must be weighed in importance by its accuracy in order to obtain accurate solutions.

Beyond this, many smaller, special studies will be useful. For example: (a) Can air-expendable bathythermographs (which measure temperature down to a few hundred meters), when dropped along an east-west line be used, together with satellite observations of topography, to estimate heat transport? (b) How often must the density field of the ocean below the thermocline be measured? (c) What is the length scale of the deeper motion? How closely must it be sampled? (d) What are the time and space scales of the topography observed by Seasat in various oceanic regions? More generally, the supporting measurement and modelling effort must be established. The existing tidal models must be improved, perhaps with the use of new, direct measurements. The atmospheric load analyses should be studied to see if they are optimum or how they might be improved. Better understanding of the wave-height algorithms must be achieved. And the best methods for processing the received altimeter pulse must be explored in order to build altimeters capable of measuring their height above a wavy surface with a precision of two centimeters.

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## REFERENCES

- Blumen, W., 1972. Geostrophic adjustment, *Reviews of Geophysics & Space Physics* **10**, 485-528.
- Bracalente, E.M., Boggs, D.H., Grantham, W.L., and Sweet, J.L., 1980. The SASS scattering coefficient ( $\sigma^0$ ) algorithm, *IEEE Journal of Oceanic Engineering* **OE-5**, 145-154.
- Bryden, H.L. and Hall, M.M., 1980. Heat transport by currents across 25°N latitude in the Atlantic Ocean, *Science* **207**(22), 884-885.
- Cartwright, D.E., 1977. Ocean tides, *Reports on Progress in Physics* **40**, 665-708.
- Cartwright, D.E., 1980. On the choice of orbit for a precise satellite-altimetry programme, (unpublished manuscript).
- Cartwright, D.E., Zeller, B.D., and Hamon, B.V., 1979. Pelagic Tidal Constants, IAPSO Publication Scientifique No. 30, Paris: IUGG Publications Office.
- Cartwright, D.E., Edden, A.C., Spencer, R., and Vassie, J.M., 1980. The tides of the northeast Atlantic Ocean, *Phil. Trans. Royal Society of London* **A298**, 87-139.
- Cfahine, M.T., 1980. Remote sensing of the atmosphere—weather and climate overview. Pasadena: Jet Propulsion Laboratory Report (unpublished manuscript).
- Chapman, M.E., 1979. Techniques for interpretation of geoid anomalies, *J. Geophysical Research*, **84**(B8), 3793-3801.
- Charney, J.G., 1955. The Gulf Stream as an inertial boundary layer, *Proceedings of the U.S. National Academy of Sciences* **41**, 731-740.
- Cheney, R.E. and Marsh, J.G., 1981. Seasat altimeter observations of dynamic ocean currents in the Gulf Stream region, *J. Geophysical Research* **86**, 473-483.
- Chester, 1981. TOPEX radiometer correction, (unpublished manuscript).
- Colquitt, E.S., Malyevac, C.W., and Anderle, R.J., 1980. Doppler computed Seasat Orbits, *J. Astronautical Sciences* **28**(4), 391-403.
- Cutting, E., Born, G.H., and Frautnich, J.C., 1978. Orbit analysis for SEASAT-A, *J. Astronautical Sciences* **26**(4), 315-342.
- Davies, K., 1978. Forecasting and prediction of ionospheric parameters, NATO: Advisory Group for Aerospace Research and Development, AGARD Lecture 93, Recent Advances in Radio and Optical Propagation for Modern Communications, Navigation and Detection Systems, pp.6-1 to 6-29.
- Davies, K., 1980. Recent progress in satellite radio beacon studies with particular emphasis on the ATS-6 radio beacon experiment, *Space Science Reviews* **25**(4), 357-430.
- Davies, K., Harmann, G.K., and Leitingner, R., 1977. A comparison of several methods of estimating the columnar content of the plasmasphere, *J. Atmospheric and Terrestrial Research* **39**, 571-580.
- Davis, R.E., 1978. Estimating velocity from hydrographic data, *J. Geophysical Research* **83**(11), 5505-5509.
- Dawson, James, 1977. Freak ocean waves are episodic, *New Scientist* **73**(1033), 7-9.
- Department of Energy, 1980. Carbon Dioxide Effects, Research and Assessment Program. Workshop on environmental and societal consequences of a possible CO<sub>2</sub>-induced climate change, CONF-7904143, UC-11, 470pp.
- Dietrich, G., 1944. Die Schwingungssysteme der half- und eintagigen Tiden in den Ozeanen, *Veroeffentl. Inst. Meerskunde Univ. Berlin* **A41**, 7-68.
- Douglas, D.C., Goad, C., Morrison, C., and Foster, F., 1980. A determination of the geopotential from satellite-to-satellite tracking data, *J. Geophysical Research* **85**(B10), 5471-5480.



- Duing, W.O. and Mooers, C.N.K., 1977. Low-frequency variability in the Florida Current and some relation to atmospheric forcing, 1972-1974, *J. Marine Research* **35**, 129-161.
- Duing, W., Molinari, R.L., and Swallow, J.C., 1980. Somali current: Evolution of a surface flow, *Science* **209**, 588-590.
- Estoque, M.A. and Fernandez-Partagas, J.J., 1980. Analysis of Seasat wind observations over the Indian Ocean. Miami: The University of Miami Technical Report TR-80-3, 55pp.
- Evans, R. and Brown, O., 1981. Propagation of thermal fronts in the Somali Current system, *Deep-Sea Res.* (in press).
- Gloersen, P., Zwally, H.J., Chang, A.T.C., Hall, D.K., Campbell, W.J., and Ramseier, R.O., 1978. Time-dependence of sea-ice concentration and multiyear ice fraction in the Arctic basin, *Boundary-Layer Meteorology* **13**, 339-359.
- Goldhirsh, J. and Rowland, J.R., 1980. Assessment of atmospheric height uncertainties for high precision satellite altimeter missions to monitor ocean currents, Baltimore: The Johns Hopkins University Report JHUV/APL SIR80U-018 (NASA CR-156868).
- Gordon, A.L. and Baker, T.N., 1980. Ocean transient as observed by Geos-3 coincident orbits, *J. Geophysical Research* **85**, 502-506.
- Harris, R.A., 1904. Physical Hydrography. Manual of Tides - pt. IVb, Cotidal Lines of the World, in Report of the U.S. Coast and Geodetic Survey, Appendix 5, Washington: U.S. Printing Office, 315-400.
- Hastenrath, S., 1980. Heat budget of tropical ocean and atmosphere, *J. Physical Oceanography* **10**(2), 159-170.
- Hendershott, M.C., 1977. Numerical models of ocean tides, in *The Sea*, vol. 6, E.D. Goldberg, I.M. McCave, J.J. O'Brien, J.H. Steele, eds., New York: Wiley-Interscience.
- Hendershott, M., 1981. Long waves and ocean tides, in *Evolution of Physical Oceanography: Scientific Surveys in Honor of Henry Stommel*, B.A. Warren and C. Wunsch eds., Cambridge: The MIT Press, 292-341.
- Hollinger, J.P., 1980. Seasat altimeter atmospheric range correction. Washington: U.S. Naval Research Laboratory Memorandum 4342, 23pp.
- Huang, N.E. and Long, S.R., 1980. An experimental study of the surface elevation probability distribution and statistics of wind-generated waves, *J. Fluid Mechanics* **101**, 179-200.
- Jackson, F.C., 1979. The reflection of impulses from a nonlinear random sea, *J. Geophysical Research* **84**(C8), 4439-4943.
- Jekeli, C. and Rapp, R., 1980. Accuracy of the determination of mean anomalies and mean geoid undulation for a satellite gravity field mapping mission. Ohio State University Geodetic Science Report no. 307.
- Johnson, J.W., Williams Jr., L.A., Bracalente, E.M., Beck, F.B., and Grantham, W.L., 1980. Seasat-A satellite scatterometer instrumentation evaluation, *IEEE Journal of Oceanic Engineering* **OE-5**, 138-144.
- Katz, E.J., 1973. Profile of an isopycnal surface in the main thermocline in the Sargasso Sea, *J. Physical Oceanography* **3**, 448-457.
- Kelly, K.A., 1980. Satellite observations of the California Current system, *EOS Transactions American Geophysical Union* **61**(46), 982.
- Kenney, J.E., Uliana, E.A., and Walsh, E.J., 1979. The surface contour radar, a unique remote sensing instrument, *IEEE Trans. Microwave Theory and Techniques* **MTT-27**(12), 1080-1092.
- King-Hele, Desmond, 1976. The shape of the Earth, *Science* **192**, 1293-1300.

- Klobuchar, J.A., 1978. Ionospheric effects on satellite navigation and air traffic control systems, NATO: Advisory Group for Aerospace Research and Development, AGARD Lecture 93, Recent Advances in Radio and Optical Propag. for Modern Communications. Navigation and Detection Systems, pp.7-1 to 7-17.
- Lambeck, K., 1980. *The Earth's Variable Rotation: Geophysical Causes and Consequences*, Cambridge University Press.
- Leetmaa, A. and Bunker, A.F., 1978. Updated charts of the mean annual wind stress in the Ekman layers, and Sverdrup transports in the North Atlantic, *J. Marine Research* 36, 311-322.
- Leitch, F., Klosko, S.M., Laubscher, R.E., and Wagner, C.A., 1979. Gravity model improvement using Geos-3 (GEM9 and 10), *J. Geophysical Research* 84, 3897-3916.
- Mariner's Weather Log, 1974. Important notice—Freak waves off South Africa, 18(5), 297-298.
- Marsh, J.G. and Chang, E.S., 1978. 5' Detailed gravimetric geoid in the northwestern Atlantic Ocean, *Marine Geodesy* 1(3), 253-261.
- Marsh, J.G., Martin, T.V., McCarthy, J.J., and Chovitz, P.S., 1980. Mean sea surface computation using Geos-3 altimeter data, *Marine Geodesy* 3, 359-378.
- Marsh, J.G. and Williamson, R., 1980. Precision orbit analyses in support of the Seasat altimeter experiment, *J. Astronautical Sciences* 28(4), 345-369.
- Mather, R.S., Coleman, R. and Hirsch, B., 1980. Temporal variations in regional models of the Sargasso Sea from Geos-3 altimetry, *J. Physical Oceanography* 10(2), 171-185.
- McKenzie, D.P., 1977. Surface deformation, gravity anomalies and convection, *Geophysics J. Royal Astronomical Society* 48, 211-238.
- McWilliams, J.C., 1976. Maps from the Mid-Ocean Dynamics Experiment: Part I, Geostrophic Stream functions, *J. Physical Oceanography*, 810-827.
- MODE Group, The, 1978. Mid-Ocean Dynamics Experiment, *Deep-Sea Research* 25, 859-910.
- Moran, J.M., and Rosen, B.R. 1980. Estimation of the propagation delay through the atmosphere from microwave radiometer data. Washington: NASA Conference Publication 2115 (Radio Interferometry Techniques for Geodesy), 363-376.
- Munk, W. and Wunsch, C., 1979. Ocean acoustic tomography: a scheme for large-scale monitoring, *Deep-Sea Research* 26A, 123-161.
- NASA, 1979. *Ice and Climate Experiment*. Greenbelt: Goddard Space Flight Center, 176pp.
- National Research Council, 1978. *Geodesy: Trends and Prospects*, National Academy of Sciences, USA, 86pp.
- National Research Council, 1979a. Carbon dioxide and climate: a scientific assessment. Washington: National Academy of Sciences, 22pp.
- National Research Council, 1979b. Application of a dedicated gravitational satellite mission, Panel on Gravity and Sea Level, Committee on Geodesy. Washington: National Academy of Sciences, 53pp.
- Needler, G.T., 1967. Models of the thermohaline circulation in an ocean of finite depth, *J. Marine Research* 25, 329-342.
- Niiler, P.P. and Richardson, W.S., 1973. Seasonal variability of the Florida Current, *J. Marine Research* 31, 144-167.
- Nowlin, W.D. and Pillsbury, R.D., 1981. Observations of kinetic energy levels in the Antarctic Circumpolar Current in the Drake Passage (to be published).
- Oort, A.H. and Von der Haar, T.H., 1976. On the observed annual cycle in the ocean-atmosphere heat balance over the northern hemisphere, *J. Physical Oceanography* 6, 781-800.

- Parsons, B. and Richter, F.M., 1980. A relationship between the driving force and geoid anomaly associated with mid-ocean ridges, *Earth and Planetary Science Letters* 51(2), 445-450.
- Pedlosky, J., 1979. *Geophysical Fluid Dynamics*, New York: Springer-Verlag, 624pp.
- Rapp, R.H., 1978. Mean gravity anomalies and sea surface heights from Geos-3 altimeter data. Columbus: Ohio State University, Geodetic Sciences Report 268.
- Rapp, R.H., 1980a. The  $1^\circ \times 1^\circ$  mean anomaly field of the Earth and prospects for its improvement. Paper presented at the symposium: Geodesy and Physics of the Earth, Karl - Marx - Stadt, GDR.
- Rapp, R.H., 1980b. A comparison of altimeter and gravimetric geoids in the Tonga Trench and Indian Ocean areas, *Bulletin Geodesique* 54(2), 149-163.
- Rhines, P.B., 1977. The dynamics of unsteady currents, in *The Sea*, vol. 5, E.D. Goldberg, I.M. McCane, J.J. O'Brien, and J.H. Steele eds., New York: Wiley, 189-318.
- Roemmich, D.H., 1981a. On the usefulness of a GRAVSAT geoid in determining ocean circulation, (unpublished manuscript).
- Roemmich, D., 1981b. Estimation of meridional heat flux in the North Atlantic using inverse methods, *J. Physical Oceanography* (in press).
- Schaper, L.W., Staelin, D.H., and Waters, J.W., 1970. The estimation of tropospheric electrical path length by microwave radiometry, *Proceedings IEEE* 58, 272-273.
- Schmitz, W.J., 1978. Observations of the vertical distribution of low-frequency kinetic energy in the western North Atlantic, *J. Marine Research* 36, 295-310.
- Schott, F.A. and Quadfasel, D.R., 1980. Development of the subsurface currents of the northern Somali Current gyre from March to July 1979, *Science* 209, 593-595.
- Schutz, B.E., Tapley, B.D., Eanes, R.J., Marsh, J.G., Williamson, R.G., and Martin, T.V., 1980. The precision orbit determination software validation experiment, *J. Astronautical Sciences* 28(4), 327-343.
- Schwiderski, E.W., 1980. On charting global ocean tides, *Reviews of Geophysics and Space Physics*, 18(1), 243-268.
- Stommel, H., Niiler, P. and Anati, D., 1978. Dynamic topography and recirculation of the North Atlantic, *J. Marine Research* 36, 449-469.
- Tapley, B.D., Born, G.H., Hagar, H.H., Lovell, J., Parke, M.E., Diamante, J.M., Douglas, B.C., Goad, C.C., Kolenkiewicz, R., Marsh, R.J., Martin, C.F., Smith III, S.L., Townsend, W.F., Whitehead, J.A., Byrne, H.M., Fedor, L.S., Hammond, D.C., and Mognard, N.M., 1979. SEASAT altimeter calibration: Initial results, *Science* 204(4400), 1410-1412.
- Tapley, B.D. and Born, G.H., 1980. The Seasat precision orbit determination experiment, *J. Astronautical Sciences* 28(4), 315-326.
- Topex Precision Orbit Determination Group, 1980. A preliminary Topex orbit accuracy analysis. Austin: University of Texas Technical Report IASOM TR 80-4, 50pp.
- Torge, W., 1980. Regional gravimetric geoid calculations in the North Sea test area, *Marine Geodesy* 3(1-4), 257-271.
- Trenberth, K.E., 1979. Mean annual poleward energy transports by the oceans in the southern hemisphere, *Dynamics Atmospheres and Oceans* 4, 57-64.
- Ulbrich, C.W. and Atlas, D., 1978. The rain parameter diagram: methods and applications, *J. Geophysical Research*, 83(3), 1319-1325.
- Veronis, G., 1969. On theoretical models of thermocline circulation, *Deep-Sea Research* 16, suppl., 301-323.
- Vonbun, F.O., 1977. Goddard laser systems and their accuracies, *Phil. Trans. Royal Society London* A284, 443-450.

- Walsh, E.J., Uliana, E.A., and Yaplee, B.S., 1978. Ocean wave heights measured by a high resolution pulse-limited altimeter, *Boundary-Layer Meteorology* **13**, 263-276.
- Watts, A.B., 1979. On geoid heights derived from Geos-3 altimeter data along the Hawaiian-Emperor seamount chain, *J. Geophysical Research* **84**(B8), 3817-3826.
- Welander, P., 1971. Some exact solutions to the equations describing an ideal fluid thermocline, *J. Marine Research* **29**, 60-68.
- Webb, D.J., 1981. A comparison of satellite and sea-surface measurements of significant wave height (submitted to *J. Geophysical Research*).
- Wunsch, C., 1972. The spectrum from two years to two minutes of temperature in the main thermocline at Bermuda, *Deep-Sea Research* **19**, 577-593.
- Wunsch, C., 1980. Meridional heat flux of the North Atlantic Ocean, *Proc. U.S. National Academy Sciences* **77**, 5043-5047.
- Wunsch, C., 1981a. Low frequency variability of the sea, in *Evolution of Physical Oceanography: Scientific Surveys in Honor of Henry Stommel*, B.A. Warren and C. Wunsch eds., Cambridge: MIT Press, 342-374.
- Wunsch, C., 1981b. An interim relative sea surface for the North Atlantic Ocean, *Marine Geodesy* (in press).
- Wunsch, C. and Gaposhkin, E.M., 1980. On using satellite altimetry to determine the general circulation of the ocean with application to geoid improvements, *Reviews of Geophysics and Space Physics* **18**, 725-745.
- Wunsch, C. and Gill, A.E., 1976. Observations of the equatorially trapped waves in Pacific sea-level variation, *Deep-Sea Research* **23**, 371-390.
- Wyrtki, K., 1975. Fluctuations of the dynamic topography in the Pacific Ocean, *J. Physical Oceanography* **5**, 450-459.
- Wyrtki, K., 1979. Sea level variation: monitoring the breath of the Pacific, *EOS Transactions American Geophysical Union* **60**, 25-27.
- Wyrtki, K., Magaard, L. and Hager, J., 1976. Eddy energy in the oceans, *J. Geophysical Research* **81**, 2641-2646.
- Yaplee, B.S., Shapiro, A., Hammond, D.L., Au, B.D., and Uliana, E.A., 1971. Nanosecond radar observations of the ocean surface from a stable platform, *IEEE Transactions Geoscience Electronics* **GE-9**, 170-174.
- Zetler, B. D., 1971. Radiational ocean tides along the coasts of the United States, *J. Physical Oceanography* **1**, 34-38.

## APPENDIX A: SOME OCEANOGRAPHIC EXPERIMENTS

Oceanography has and will tend to emphasize the study of particular regions for a variety of important reasons. We note here a few examples of such areas where a TOPEX mission could make a direct contribution to such focussed problems. These particular experiments would occur in addition to the global-scale problems addressed by TOPEX, and would be embedded in them. We make no pretense to doing anything more than listing a tiny fraction of the actual possibilities.

### A.1 Equatorial Region

The equatorial regions of the world's oceans are special. They appear to be more directly coupled to the atmosphere and to have a much stronger and more obvious influence on climate than do the mid-latitude oceans. They are dynamically distinct, and contain such features as undercurrents and equatorially trapped waves. Furthermore, the equatorial Pacific gives rise to the dramatic El Niño phenomenon with consequences for both fisheries and climate. The increasing information that the El Niño phenomenon is basin wide in the Pacific Ocean is just one example of the importance of establishing the circulation pattern over all of the Pacific Ocean.

At the present time, at least two major national programs, PEQUOD and EPOCS, are concentrating on the East-Central Pacific Ocean and an additional smaller effort, SEQUAL, exists in the Atlantic. These and succeeding programs are expected to continue through the rest of the decade. By measuring the topography of the equatorial oceans, TOPEX could have a major impact on these studies. For example, persistent easterly winds produce a zonal pressure gradient along the equator with pressure increasing toward the west. Isotherms in the upper ocean tilt upward toward the east and an undercurrent flows eastward down the pressure gradient, which occurs almost entirely in the upper layers because of the strong stratification. Because the strength of the easterly wind varies throughout the year, variations of the zonal pressure gradient and of the strength of the undercurrent are also expected.

The sea surface is about 50 cm higher in the western Pacific than in the east and the sea surface slope along the equator is not uniform. In the Pacific the slope is largest between 125°W and 155°W; east of 120°W it is essentially horizontal (figure A.1). The sea surface fluctuates with periods much longer than the tides, and interannual variations of monthly sea level may be as large as  $\pm 20$  cm (Wyrski, 1979).

The meridional distribution of sea-surface elevation in the tropical Pacific contains variations that correspond to the boundaries of the major zonal currents (Wyrski, 1979). Sea level differences as large as 30 cm over 500 km might occur between 5°N and 10°N. Because the current systems are relatively thin with virtually all of the flow occurring above the thermocline, the sea-level gradient determines the geostrophic flow in the upper layer.

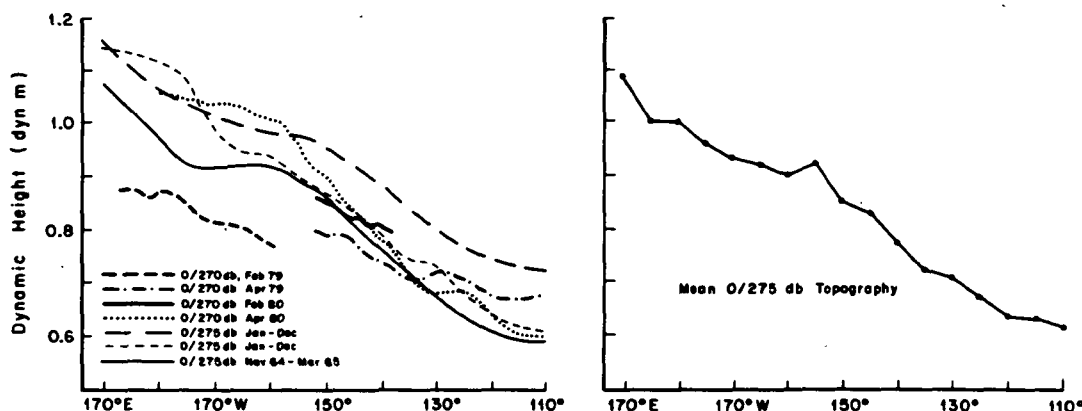


Figure A.1 Dynamic height of the sea surface along the equator in the Pacific Ocean determined at different times of the year (left), and averaged over all data (right). Note that one dynamic meter is approximately one meter of surface elevation.

Monitoring these zonal and meridional slopes in sea level is currently possible only by using instruments on oceanic islands and along the continents, but major portions of the equatorial oceans are devoid of islands (figure 2.2). The South Pacific is the region with the least data on circulation. Aside from the hydrographic sections from the Scorpio Expedition, the information from hydrography, sea level, and bathythermographs is essentially nil; and over most of the region, islands and commercial shipping lanes are relatively sparse. Therefore, the only feasible sources of information would be a combination of satellite-based altimetry and surface drifters of various types. Were such data available, they would complement existing equatorial studies, and would allow the determination of the sea-surface topography and circulation throughout the tropical Pacific.

## A.2 Western Indian Ocean

The Somali Current has the strongest near-surface currents of all open-ocean current systems; and it generally reverses direction under the influence of the monsoon. Recent measurements have revealed very puzzling features of this boundary current. Instead of flowing along the coast from south of the equator to 10°N according to conventional wisdom, the current can split into two gyres separated by a cold upwelling wedge (figure A.2). Offshore flows of up to six knots were observed in 1979; but the surface-elevation signature, despite the very strong currents, is only a few decimeters due to proximity of the equator. Satellite observations of sea-surface temperatures (Evans and Brown, 1981) show that late in the summer monsoon the southern cold-water wedge may travel north at significant speeds and merge with the northern wedge, indicating a breakdown of the two-gyre circulation into a continuous coastal current (figure A.3). In addition, moored current-meter observations (Schott and Quadfasel, 1980) have revealed waves with periods of one to two months which propagate into the Somali Current system and may contribute to its further development after onset.

The development of the Somali Current differs considerably from year to year, and the current system will continue to raise important questions concerning its response to the monsoon and its influence on the climate of adjacent regions. Through its ability to measure surface topography, TOPEX would therefore be extremely useful for further monitoring of this system. However, study of the Somali Current also requires satellite observations of wind. At the height of the monsoon with 40 knot winds off Somalia, up to 30% of the total transport, which amounts to  $40 \times 10^6 \text{ m}^3/\text{s}$  in the upper 400 m in the northern part of the current, is directly driven by the wind *i.e.*, is nongeostrophic and cannot be derived from altimetry and density measurements.

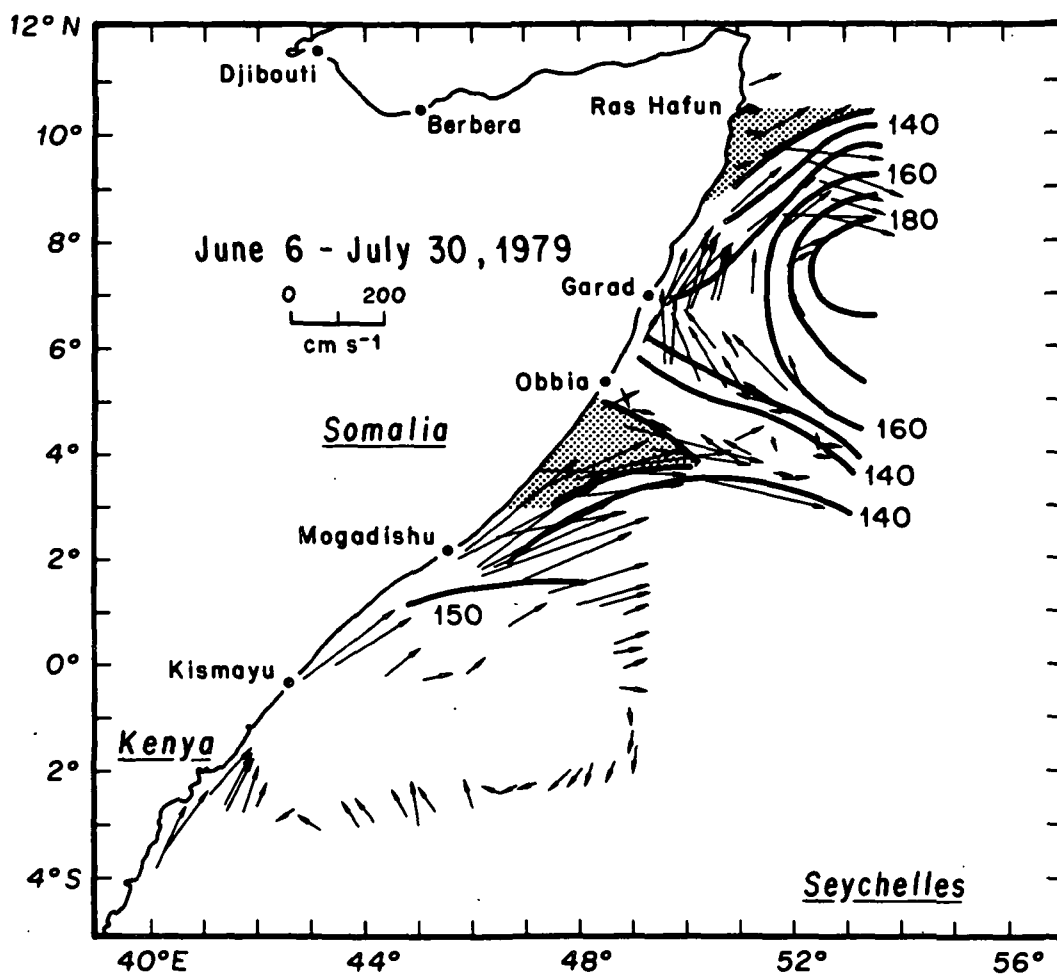


Figure A.2 Surface currents measured by ships during June 6 - July 7, 1979 in the Somali Current system (after Duing *et al.*, 1980). Also indicated are cold-water wedges and surface topography relative to 1000 dbar.

### A.3 A Global Sea-Level Network

Wrytki (1975, 1979) has demonstrated that the variable ocean circulation can be studied using the tide-gauge network on islands in the Pacific (figure 2.2). We anticipate that this network will remain in place throughout the decade, that TOPEX will greatly enhance its value, and that, in turn, it will contribute significantly to the design of TOPEX.

It is essential to think now in terms of a global sea-level network consisting of instruments on islands distributed throughout the world's oceans. Such a network would serve to calibrate the TOPEX system by providing independent measurements of both the topography and the patterns of variability near the gauge. In turn, the TOPEX altimeter could interpolate between the island gauges and extrapolate over the vast regions of the ocean where there are not suitable islands. Examples of such areas are the Western Tropical Pacific, the South Pacific, the Southern Ocean, and the equatorial Indian and Atlantic Oceans. Such a sea-level program would allow foreign participation in TOPEX at relatively little cost and would strengthen the global aspects of use and calibration.

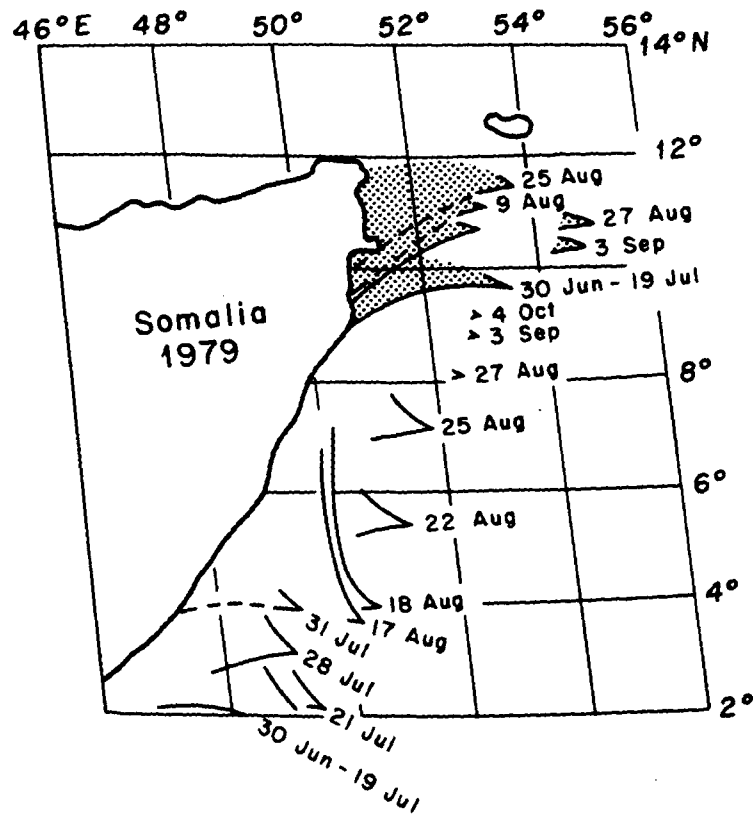


Figure A.3 Time sequence of satellite observations of the locations of northern and southern frontal wedges in 1979 (from Evans and Brown, 1981).



## APPENDIX B: ORBITS

The usefulness of a satellite altimeter depends, to a large extent, on the characteristics of the satellite's orbit. The inclination of the orbit determines the oceanic areas that can be viewed by the satellite. The semi-major axis (or orbital period) determines the way that the surface is sampled in time and space. And the forces which act on the satellite, and thus the accuracy with which the orbit can be computed, are a function of satellite height. Accuracy, coverage, and sampling are all interrelated; and all cannot be optimized by a particular orbit. Selecting an orbit requires weighing the usefulness of one orbital attribute against the usefulness of another. But foremost among the attributes is accuracy. In order for an altimetric satellite to measure ocean-surface currents, the radial component of the satellite's orbit must be known with an accuracy of five centimeters over a distance of ten thousand kilometers, and with better precision over lesser distances, an accuracy and precision that are about a factor of ten better than the best present capability (table B.1). (For more details, see the report of the TOPEX Precision Orbit Determination Group, 1980).

Achieving the desired accuracy in the determination of the TOPEX orbit will require an orbit and a satellite design carefully selected to reduce unknown forces on the satellite, an improvement in our knowledge of Earth's gravity field which we expect will come from the Gravsat program, a worldwide satellite-tracking and geodetic network which could be shared with the Crustal Dynamics Program, and improved methods for calculating satellite orbits using all available data including that from the satellite's altimeter.

In the following discussion we will consider the general sources of inaccuracy in the determination of a satellite orbit, a particular orbit best suited for TOPEX, and the expected accuracy of the determination of this particular orbit.

Table B.1 Accuracy of Geodetic Satellite Orbits

Satellite	Inclination	Height (km)	Area/Mass (m <sup>2</sup> /kgm)	Radial Orbit Error (m)
Geos-3	115°	840	$4.1 \times 10^{-3}$	1.0 - 2.0
Lageos	110°	5900	$0.7 \times 10^{-3}$	0.3 - 0.4
Starlett	50°	800-1100	$1.0 \times 10^{-3}$	1.5 - 2.0
Seasat	108°	800	$11.4 \times 10^{-3}$	0.7 - 2.5

## B.1 Sources of Error in Determining Satellite Orbits

To a first approximation the orbit of a satellite is an ellipse, but for topographic measurements this approximation is not sufficiently precise and the forces which perturb this orbit must be considered. In order of relative importance as sources of error, these are:

- (a) The lack of spherical symmetry in Earth's gravity field,
- (b) Atmospheric drag,
- (c) Solar and terrestrial-radiation pressure,
- (d) Outgassing from the satellite,
- (e) The perturbing effects of oceanic tides, and
- (f) The gravitational attraction of the moon and the sun.

The gravitational attraction of other planets and relativistic effects (non-Newtonian mechanics) are small enough to be neglected.

Because of the uncertainty in the knowledge of the forces which perturb the orbit of a satellite, its motion must be observed or tracked, and the position and velocity of the satellite estimated at some point in the observation interval. The estimate of position and velocity is then used to predict past and future positions. However, the estimates of position become less accurate with time, and the procedure must be repeated at intervals which depend on the ability to estimate both the forces on the satellite and its position and velocity. Typically this is done every few hours to every few days.

Satellite motions can be measured by a number of different systems, including radios which measure range and range rate, and lasers which measure instantaneous range to satellites when skies are clear. The tracking stations can be at fixed positions on Earth, or on a higher satellite in an orbit less influenced by perturbations in Earth's gravity field or atmosphere. The latter measurement is known as "satellite-to-satellite" tracking.

The accuracy and frequency of the range or range-rate measurements depend on the measurement system. For example, lasers can estimate ranges to satellites with an accuracy of  $\pm 5$  cm (Vonbun, 1977), and proposed modifications to contemporary radiometric tracking systems may result in all-weather measurements of range with an accuracy of  $\pm 10$  cm. In addition, the altimeter itself makes repeated measurements of its height above the ocean surface, and altimeter measurements at points where the orbital tracks cross can be used to improve the accuracy of the calculations of the orbit. Future super-high-frequency (10 GHz) radio ranging systems, which may be able to track satellites with a precision of one to five centimeters, have been proposed. When coupled with simultaneous radiometric observations of atmospheric water vapor, they may track satellites with centimeter accuracy even through clouds.

Two classes of error influence the estimates of the position of the satellite in its orbit: (a) errors in measurement of the satellite's position, and (b) errors in estimating the forces acting on the satellite. Included within the class of measurement errors are:

(a) *Atmospheric and ionospheric uncertainties*—the inability to know accurately the velocity of radiation in the atmosphere and ionosphere. The mass of the atmosphere, water vapor, and electron density contribute an uncertainty of a few parts per million in the velocity of radiation at the super-high radio frequencies used by radio tracking stations.

(b) *Station positions*—the inability to know the precise location of the tracking stations relative to the center of Earth. At present, these are known with an accuracy of twenty to thirty centimeters for the primary laser tracking stations, and fifty to one hundred centimeters for the radio tracking stations. In addition, the station positions are

influenced by polar motion and the variations of the length of the day, and these influences must be included in the computation of station coordinates.

(c) *Station distribution*—the inability to have many stations well distributed around Earth. The laser stations tend to be concentrated in the northern hemisphere and on continents rather than distributed uniformly around the Earth.

(d) *Satellite mass variations*—the mass of satellites varies because of outgassing and because of mass expelled during maneuvers. This change in mass not only changes the position of the satellite's center of mass (which is the point of reference for the orbit computation), but it also enters directly into the dynamical computations of the orbit.

The predominant errors in estimating the forces acting on a satellite in near earth orbit, include:

(a) *Gravitational potential*—the uncertainty in the knowledge of the gravitational field, at satellite heights, due to variations in the distribution of Earth's mass. At present only the lower-order harmonics of the spherical-harmonic expansion of Earth's gravity field are known relatively well.

(b) *Unknown forces*—including atmospheric drag and pressure due to solar radiation and upwelling radiation from Earth. Depending on the mass and area of the satellite, the satellite's acceleration can vary between  $10^{-8}$  and  $10^{-10}g$  over times of minutes to years, depending on solar activity, sunspot intensity, the distribution of Earth's albedo, and the satellite's reflectivity and orientation.

The two classes of error influence the determination of satellite orbits in different ways. The measurement errors influence estimates of the original position and velocity of the satellite, and the dynamic errors introduce uncertainties into the equations used to predict motion away from the original position. Therefore, the latter contribute errors in predicted position that grow with time, and new observations of position must be continuously introduced into the calculation to limit the growth of error in the predicted orbit.

## **B.2 Options for a TOPEX Orbit**

For TOPEX, we require an orbit that can be calculated to high accuracy, that provides adequate coverage of the world's oceans, that is not synchronous with the dominant oceanic tides, that has a ground track that exactly repeats every ten days, and that does not unduly compromise the altimeter design. These considerations lead to a nearly circular orbit with a particular height and inclination described below.

### **B.2.1 Advantages of High Orbits**

(a) For orbits above 1300 km, errors due to the effect of atmospheric drag will be on the order of one to three centimeters for a satellite of optimum configuration, and will not be a limiting error.

(b) When drag is small, the orbit of the satellite decays more slowly and orbit adjustments (maneuvers) necessary to maintain a selected ground track will be less frequent.

(c) The amount of time during which a station can track a satellite is greatly increased as the height of the orbit increases. Not only can the satellite be seen more frequently, but it can also be tracked over longer arcs, both of which lead to better estimates of the satellite orbit. Figure B.1 shows the distances over which a satellite can be seen from a tracking station on the ground, and figure B.2 shows areas over which a satellite at 1300 km can be tracked by laser stations in the Pacific.

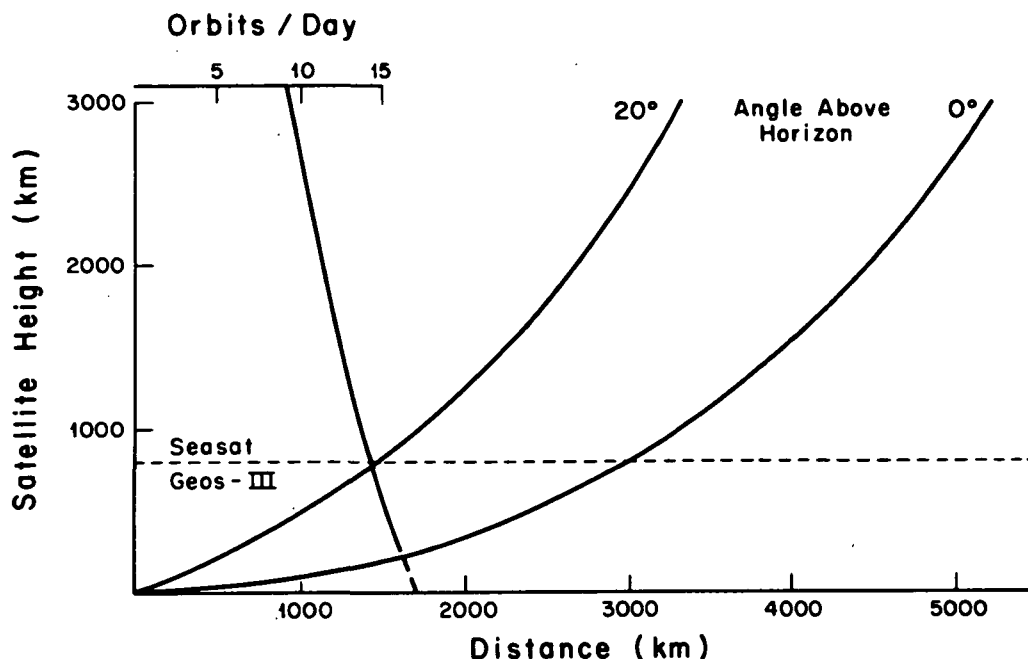


Figure B.1 Distance to which a satellite of given height and angle above the horizon can be tracked, together with the number of orbits per day as a function of height of the satellite.

### B.2.2 Advantages of Lower Orbits

(a) In order to perform as well as an altimeter in a lower orbit, an altimeter operating in higher orbit must have more power, or a more directional antenna, or a more sensitive receiver, or a combination of the three. Thus increasing the height by a factor of three requires an increase of 27 in power, or an antenna 3.7 times larger, or a receiver 27 times more sensitive. In practice, all three can be improved, but with an increase in cost and complexity of the spacecraft.

(b) At lower orbits, the rate at which a satellite maps topography is increased. The altimeter traces out a line on the sea surface whose length in one day is inversely proportional to the satellite's period. The period, in turn, varies as the three-halves power of the height of the satellite above Earth's center, and a convenient measure of the amount of sea surface surveyed by the satellite is the number of orbits per day (figure B.1). This is a weak function of height, and increasing the height of the satellite by a factor of three, from 800 to 2500 km, only decreases the orbits per day by 30%, from 14.7 to 10.4.

(c) The area of sea surface which reflects the altimeter pulse (its footprint) increases as the square root of the height of the satellite above the surface. For Seasat at 800 km this area was a circle with an approximate diameter of 2.5 km. Increasing the altimeter height by a factor of three will increase this to roughly 4.4 km for smooth surfaces. If the ocean surface is covered with three-meter-high waves, the diameter is further increased to around seven kilometers.

(d) The radiometer used to correct the altimeter signal has a rather large field of view, and the higher the satellite the larger the atmospheric area viewed by the instrument. The error introduced by observing an area which must necessarily be larger than the altimeter footprint is reduced by a lower orbit.

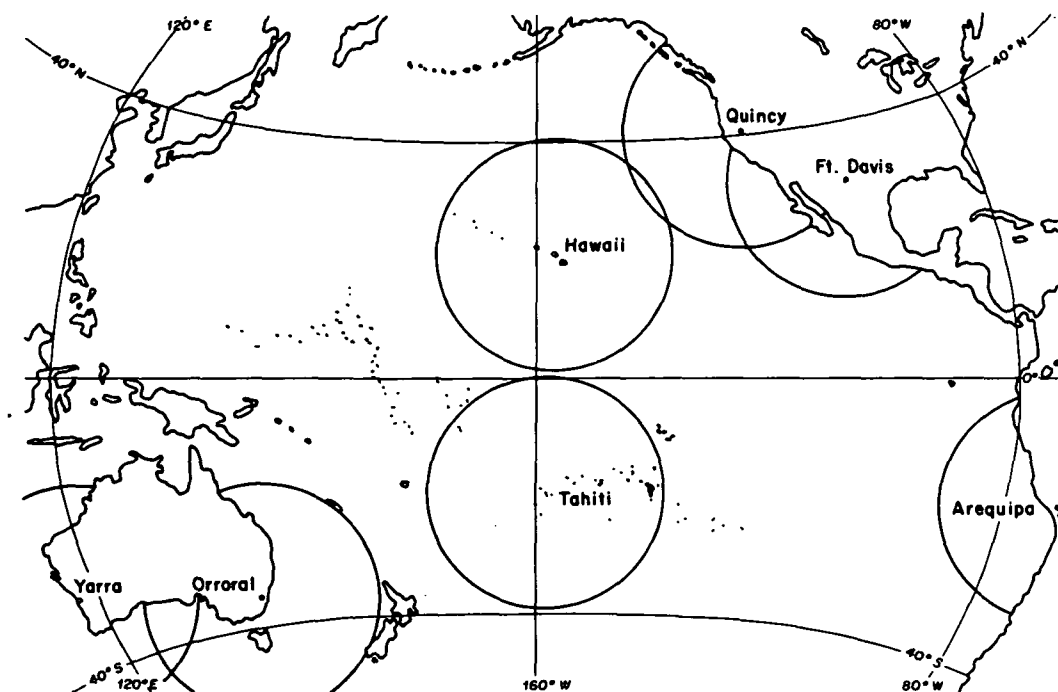


Figure B.2 Limits of laser tracking for satellite at 1300 km and 20° above the horizon, showing possible coverage in the Pacific.

### B.2.3 Orbit Selection

Four important properties of an orbit are the latitudinal extent of the grid traced out by the subsatellite point (track), the density of the grid, the time interval between repetitions of this grid, and the angle between the tracks at their intersections.

In order to sample as much of the ocean's surface as possible, the orbit should have an inclination as close as possible to 90°. However, this polar orbit has ground tracks that are nearly parallel (figure B.3), and this conflicts with the requirements that the subsatellite tracks cross at large angles in order to measure both components of the surface geostrophic current.

A reasonable compromise between good crossing angles and good coverage is an orbit with inclination near either 65° or 105°. These orbits have ground tracks that intersect at angles near 40° at the equator, and that cover most of the open water in both hemispheres (it excludes the Norwegian Sea and parts of the Southern Ocean, but these compromises seem both necessary and reasonable).

The selection of orbital inclination is also strongly influenced by a desire to avoid orbits that are nearly synchronous with the sun, so that the ocean surface is not sampled in phase with any of the major tidal constituents. To sample synchronously would alias the tidal constituents into long periods typical of the oceanic circulation, and would make it very difficult to separate the tides from the circulation. The rate at which the orbital plane precesses  $\dot{\Omega}$  is a function of inclination  $i$  and geocentric height  $a$ , given by

$$\dot{\Omega} = 1.32 \times 10^{18} a^{-7/2} \cos i \quad (\text{SI units})$$

Orbits with inclinations between roughly 65° and 115° and at heights between 1000 and 2500 km are all nearly synchronous with one or another dominant tidal constituent (figures B.4 and B.5), and should be avoided. For this reason, it is preferable to choose an orbit with inclination less than 65°. Orbits at this inclination precess at a rate greater than one degree per day relative to the sun (figure B.5), and are not close to being

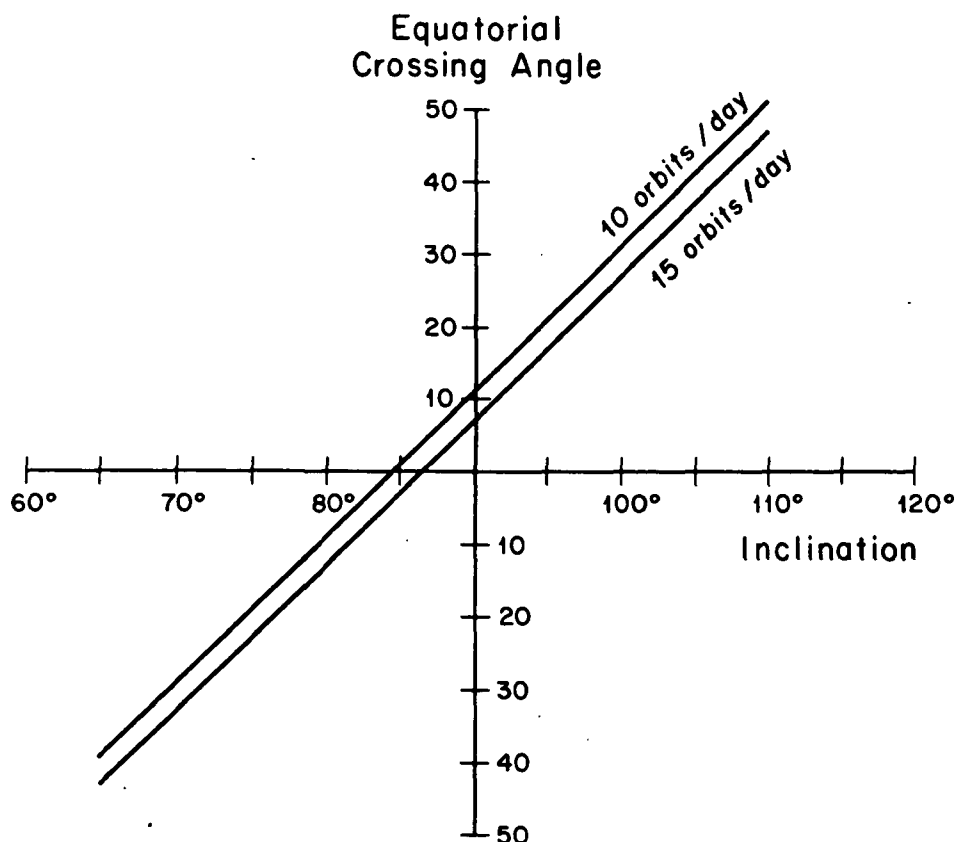


Figure B.3 Angle between intersections of subsatellite track as a function of orbital inclination with number of orbits per day as a parameter.

synchronous with any tidal constituent. We note that Seasat, at 800 km and 108° inclination precessed only 1°/day relative to the sun. As a consequence, it aliased the P1 tides to zero frequency, and the S1 and T2 tides into a cycle per year.

In order to minimize the influence of the geoid measurements of oceanic topography, and in order to sample the oceanic variability without ambiguity, the satellite's orbit should exactly repeat every 10-30 days. In general, there is always an orbit close to the desired height and inclination that exactly repeats every  $N$  days and that lays down a subsatellite track in a useful manner (Cutting, Born, and Frautnich, 1978). All that is required is that the orbital period be a suitable rational number; and provided that the repeat time is longer than a few days, many orbits are available.

The density of the grid is set by the time interval between exact repeats of the grid, the longer the interval the tighter the grid. The spacing between satellite tracks at the equator is the equatorial circumference (40,000 km) divided by the number of days between repeats and the number of orbits per day. A satellite at 1300 km makes 12.9 orbits per day and has a spacing of 3100 km between tracks at the equator. This distance decreases approximately as the cosine of the latitude (scaled by the inclination) and is approximately 2700 km at 30°. If the orbit repeats after  $N$  days, the spacing between tracks is  $D = 3100/N$ , and  $N$  determines both the temporal and the spatial sampling rates. For example, if  $N = 10$  days, the respective rates are 10 days and 270 km at 30° latitude.

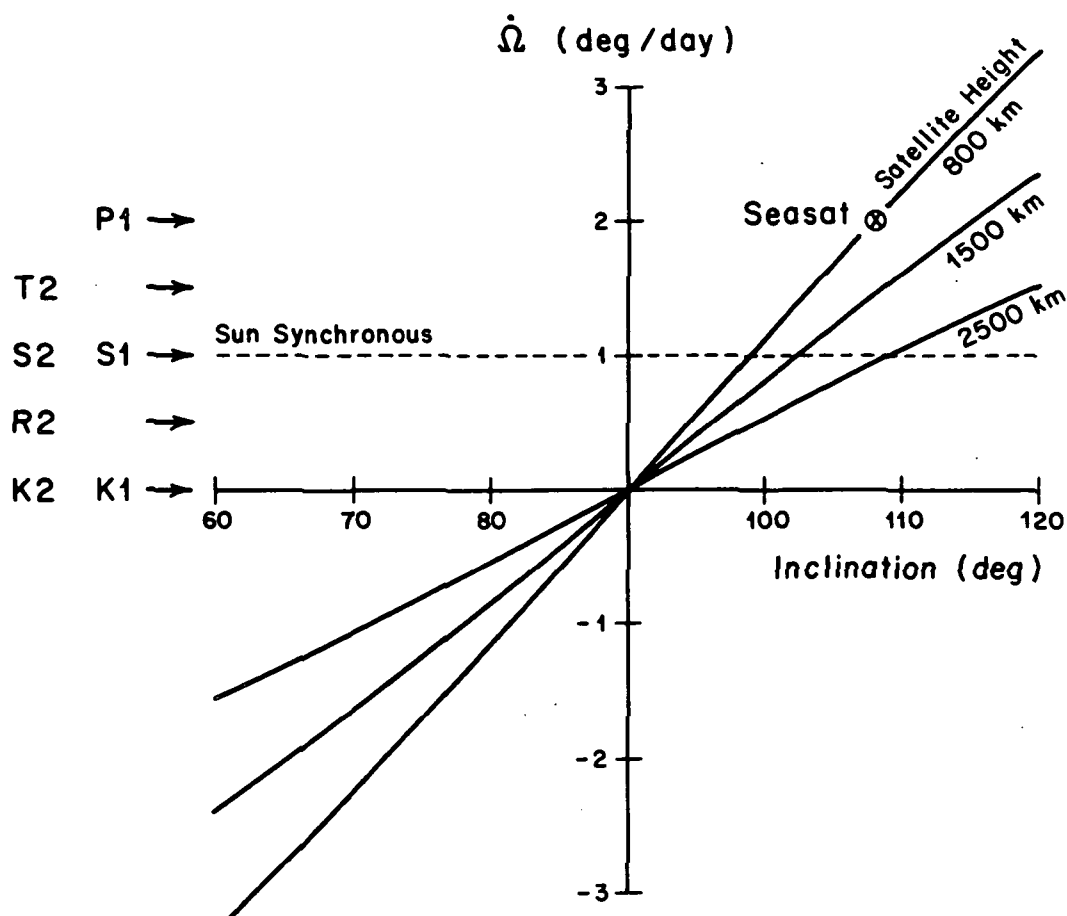


Figure B.4 Precession rate of the orbital plane as a function of inclination, with height of the satellite as a parameter. To avoid aliasing the diurnal (K1, S1, and P1) and semidiurnal (T2, S2, R2, and K2) tides into long periods, orbits which are nearly sun synchronous are to be avoided. The indicated precession rates are those which alias the designated tidal constituent to zero frequency.

#### B.2.4 Summary

The major constraints on the satellite orbit are sketched in figure B.6, and only one orbit is clearly useful, one with a height of 1300 km and an inclination of near 63°. Such an orbit is not strongly influenced by atmospheric drag, is not synchronous with the dominant tidal constituents, can observe almost all the open water on Earth, and can resolve the two components of current at mid-latitudes. Furthermore, there are many orbits near this that exactly repeat every ten days. One particular orbit at a height of 1334 km and an inclination of 63.43° has the exactly repeating ground tracks shown in figures 5.1 to 5.4.

#### B.3 The Accuracy of a TOPEX Orbit

The predominant unknown forces influencing a near-earth satellite can be separated into those resulting from uncertainties in gravity, atmospheric drag, and solar radiation pressure. A preliminary analysis of the effect of these influences on a proposed TOPEX satellite is given by the TOPEX Precision Orbit Determination Group (1980). The report assumes a spherical satellite having an area-to-mass ratio of 0.004 m<sup>2</sup> (an assumption compatible with the design used for the Geos-3 spacecraft), orbiting at an altitude of 1300 km and an inclination of 65°, and tracked by a

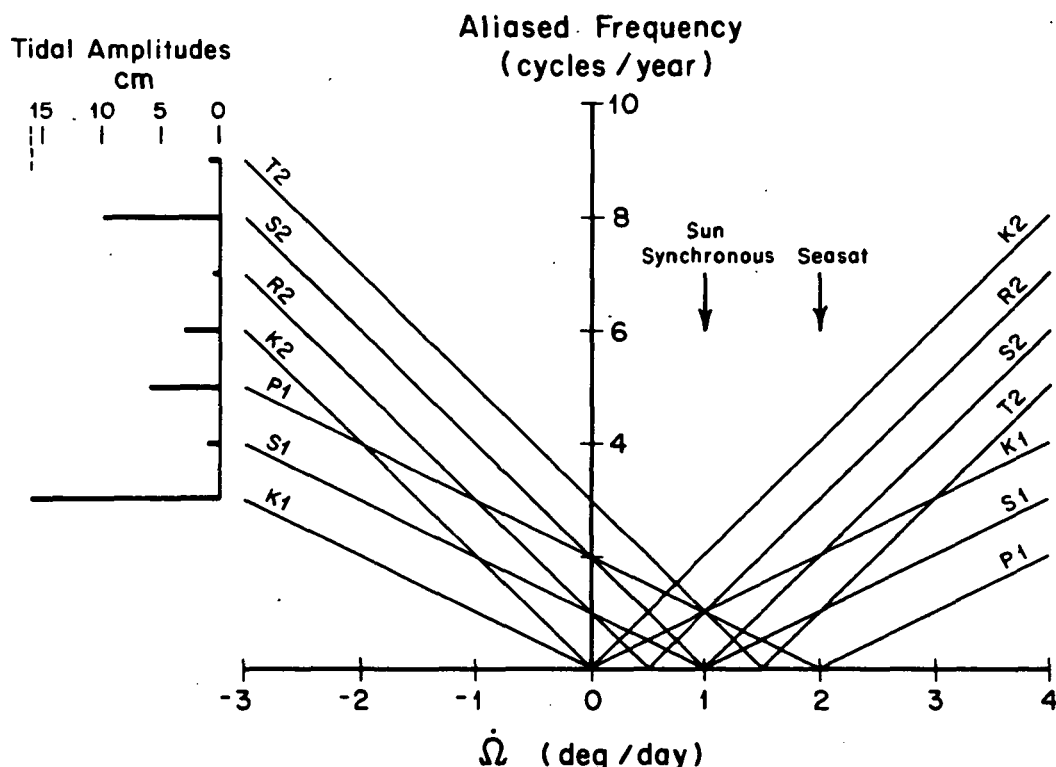


Figure B.5 Frequency into which the major tidal constituents are aliased as a function of the precession rate of the orbital plane, together with rough estimates of the tidal amplitudes (typical of the North Pacific). Note that, for sun-cynchronous orbits, S1 and S2 are aliased to zero frequency, and that T2, P1, K1, and R2 are all aliased into the same frequency of one cycle per year. Clearly such orbits must be avoided if a satellite is to study ocean circulation.

contemporary laser tracking network having a realistic distribution of stations and of tracking success (assumed to be on order of 30%).

The results of this study are summarized in table B.2. This table gives pessimistic and optimistic values for the maximum radial error due to each of the error sources examined, as well as the expected impact of the proposed Gravsat mission. Because the numbers in the table depend not only on there being no significant variations in the area of the satellite (the result of the assumption of a spherical satellite), but also on the satellite being dense, these will place severe requirements on the design of the satellite.

Because the errors listed in the table are considerably smaller than the errors in the Seasat orbit, it is worth noting the reasons. Basically, that satellite had a high area-to-mass ratio, large variations in the area presented to the sun and the atmosphere (leading to difficulties in estimating the force of radiation and drag), and a very limited amount of laser-tracking data. Despite these difficulties, the error in the radial component of the computed orbit was on order 1.4 m, an error that is substantially smaller than that for any other satellite orbit. This experience with Seasat has led to a better understanding of the limitations and errors inherent in computing accurate satellite orbits, experience useful for the present discussion.

The following conclusions result from the investigation of the errors to be expected from a TOPEX mission:



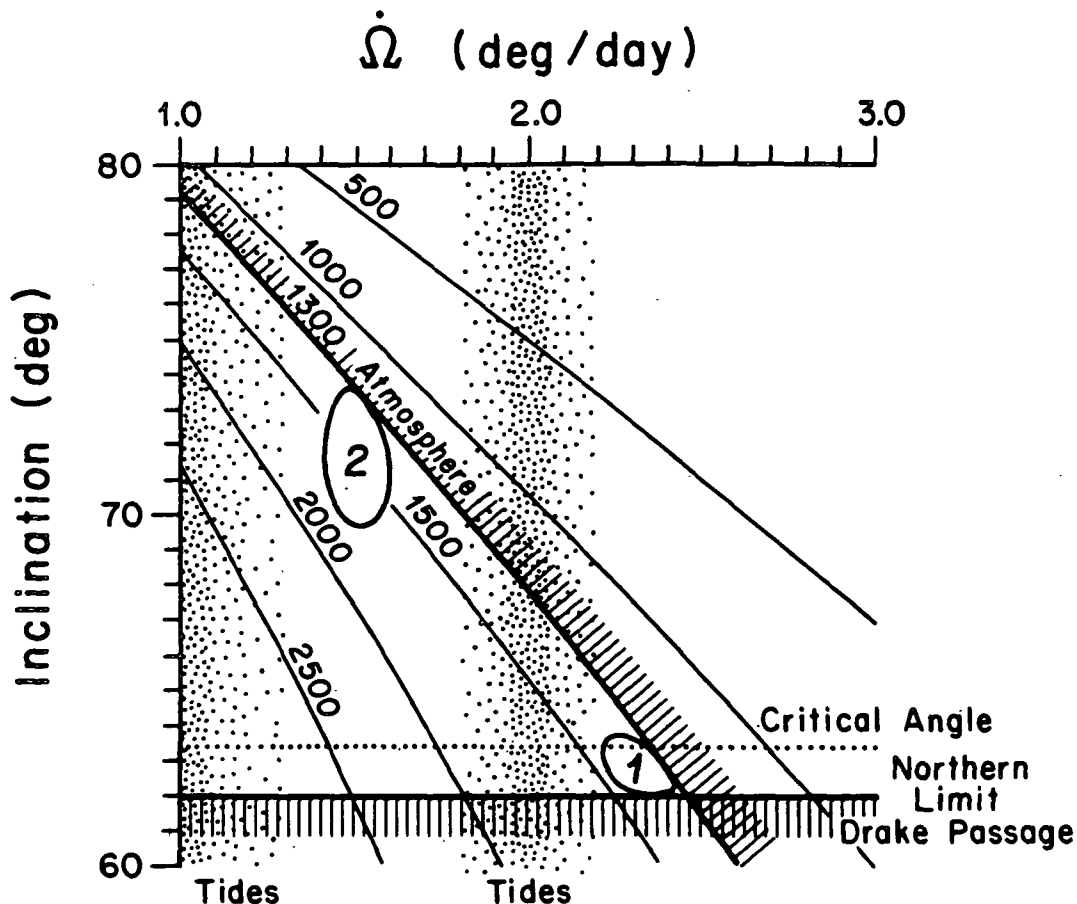


Figure B.6 The available orbits that are above the influence of the atmosphere, that precess at a rate not close to synchronous with the major tidal constituents, and that give good spatial coverage of the world's oceans. The orbit (1) with inclination near  $65^\circ$  and height near 1300 km is preferred for TOPEX. Another orbit (2) with an inclination near  $70^\circ$  is also useful, but has a smaller angle between tracks, and less separation between the aliased tidal frequencies.

(a) The dominant error in the radial component of the orbit is due to unknown gravitational forces. These are expected to contribute an error with an amplitude of 30 to 70 cm and with a frequency of once per revolution. The magnitude of the once-per-revolution error can be reduced by improving ground-based tracking or by improving the knowledge of the geopotential field; and data from Gravsat may eliminate gravity as a source of error. If there is any significant error in the gravity field, then the optimistic values in table B.2 must be revised accordingly.

(b) The second most significant error is due to the effects of solar radiation pressure. Without error due to gravity, the coefficient of radiation pressure can be recovered with sufficient accuracy that the amplitude of the radial error will be two centimeters, over arc lengths of a day, assuming a spherical satellite, nominal tracking data, and maximum shadow. The value of two centimeters is the maximum value which occurred at the end points of the arc. The error is linearly proportional to the arc length, and can be reduced by reducing the arc length; but this will require more dense tracking of the satellite. The error is also directly proportional to the satellite area-to-mass ratio and can be decreased by decreasing the projected cross-sectional area or by increasing the mass. The numbers are optimistic in the sense that they assume no

Table B.2 TOPEX Ephemeris Error Budget

Error Source	Without Gravsat		With Gravsat	
	Pessimistic	Optimistic	Pessimistic	Optimistic
Drag coefficient	2	1	2	1
Air density	3	1	3	1
Reflectivity	30	9	7	2
Earth albedo	3	1	1	1
Gravity	70	30	--	--
Station coordinates	6	2	3	1
Ocean tides	1	1	1	1
Standard error	77	32	9	3

Note that all values are given in centimeters, and assume an area-to-mass ratio of  $0.004 \text{ m}^2/\text{kg}$ . The values reported here also assume that the residual gravity error after a Gravsat mission will be negligible. Further investigation is required to establish the accuracy with which Gravsat will determine the low degree and order geopotential terms.

error due to unknown time-dependent variations in the satellite area. This caveat imposes an additional requirement on the satellite design, *i.e.*, any time dependent variation in the area must be accurately known.

(c) The errors in drag and radiation coefficients are actually the errors in the products of the coefficients times the area-to-mass ratio. Thus the ability to estimate these coefficients is directly linked to the accuracy with which the area-to-mass ratio is known; and the results indicate that the ratio must be kept below  $4 \times 10^{-3} \text{ m}^2/\text{kg}$ .

(d) The assessment of the error due to poor estimates of the drag was directed specifically at evaluating the effects of errors in both the drag coefficient and in the estimates of atmospheric density. The effect of errors in the parameters used to calculate atmospheric density (*e.g.*, solar flux and geomagnetic indices) was found to cause errors of less than one centimeter for a 5% uncertainty in these parameters. Furthermore, the correct value for the drag coefficient can be estimated accurately if there is no significant error in the geopotential.

(e) The assumption that each tracking station coordinate will be known to ten centimeters leads to an orbit error on the order of one to three centimeters. The ten centimeter accuracy in station coordinates is based on the assumption that the Crustal Dynamics Program will provide coordinates for the tracking stations to this level of accuracy by 1985. In addition, we expect that the program will also provide accurate estimates for polar motion and Earth rotation rates.

(f) Finally, the values quoted in the table are the maximum values. The dominant errors have a frequency of once per revolution, and the typical error at other points in the orbit will be less than the maximum value. Furthermore, the errors due to drag and radiation pressure are reported in terms of the amplitude of the once per

revolution error at the end points of the orbital arcs. Reporting all the errors as standard errors would reduce the quoted values by 20 to 40%.

In conclusion, we have assumed that the geopotential field will be known from the Gravsat program. Thus the dominant radial error in the orbit will be due to the effect of solar radiation. To achieve the required five centimeter accuracy in the radial component of the orbit, an area-to-mass ratio of  $0.004 \text{ m}^2/\text{kg}$  is required. Should such a density not be possible, then great care must be taken to assess accurately the influence of radiation pressure if the orbital errors are to be kept as low as the quoted values.

## APPENDIX C: AUXILIARY GEOPHYSICAL STUDIES

The primary goal of this report has been to investigate the usefulness of satellite altimeters for measuring geostrophic surface currents. Nevertheless, satellite systems designed to measure currents also produce information useful for other geophysical studies. An altimeter can measure variations in sea level near coasts due to tides and storm surges, can profile the shape of continental glaciers, and can map the topography of plains. The reflected altimeter pulse contains information about the roughness and composition of Earth's surface, information that can be used to deduce wind speed, wave height, the existence of ice cover over the oceans, and the type of snow cover on glaciers. Auxiliary observations used to correct the altimeter signal measure water vapor in the atmosphere and free electrons in the ionosphere. And information contained in the leading edge of the reflected altimeter pulse can be used to measure rain just above the sea surface on occasions when moderate to heavy rain is present.

To some extent, these phenomena will also be observed by Noss, and TOPEX will serve mainly to supplement these more extensive observations. But to some extent, the TOPEX observations will be unique. They will increase the probability of observing rare but important phenomena such as storm surges or tsunamis, and they will offer the possibility of studying phenomena not readily observed by other programs.

### C.1 Types of Auxiliary Measurements

Before considering a few of the more important geophysical studies that might be aided by the TOPEX observations, it is useful to specify in more detail the types of auxiliary information that will be provided by instruments on the satellite. This information is derived primarily from the shape and amplitude of the reflected altimeter pulse, the difference in height measured by altimeters operating at two different radio frequencies, and the amount of radio energy received by the microwave radiometer.

The primary altimeter measurement is the height of the satellite above the sea surface. In normal operation the altimeter searches over a narrow band of ranges for the leading edge of the reflected pulse, and then tracks the edge as it varies in range. Over sloping glacier ice and over land the edge is very diffuse compared with reflections from the sea, and the altimeter can neither find nor easily track it. However, with some modifications to the signal-processing circuitry the altimeter on TOPEX should be able to track the height of the satellite over smoothly sloping surfaces such as the Antarctic Continent, Greenland, and the plains of Florida.

The shape of the reflected altimeter pulse is determined by the distribution of wave heights at the sea surface. The very short pulse characteristic of radar altimeters is reflected first from wave crests and later by the troughs, and is stretched by an amount proportional to wave height and skewness. The technique has been used to measure ocean waves from space using altimeters on both Seasat and Geos-3, the

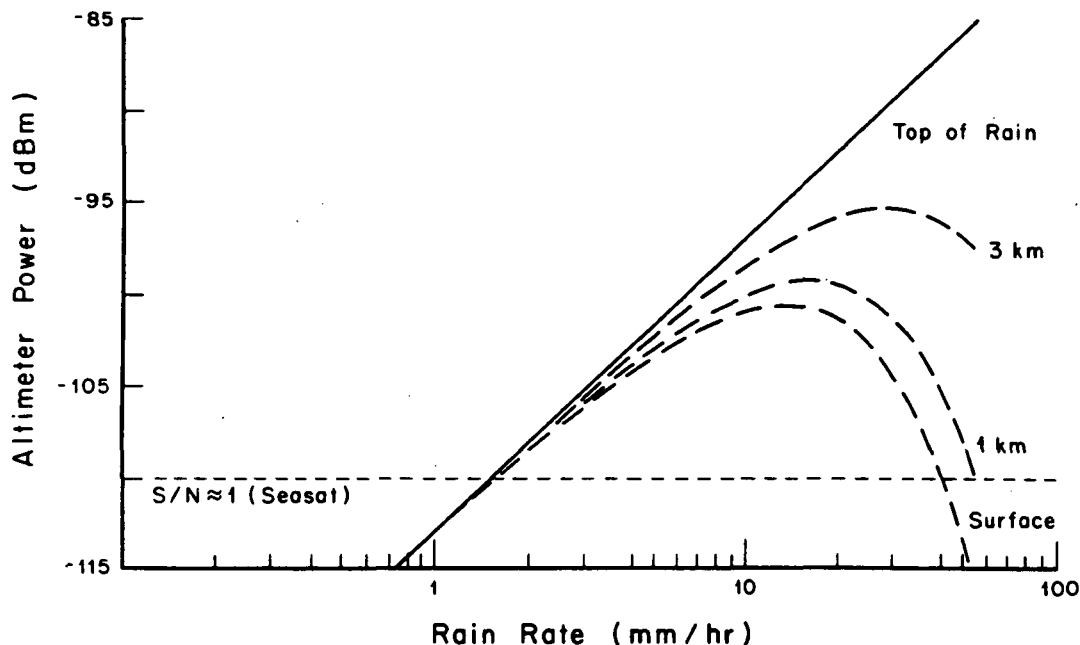


Figure C.1 Altimeter power backscattered from rain as a function of rain rate with the height of the scattering region as a parameter.

former producing the more accurate observations because of its shorter pulse. Provided the wave height is greater than about one meter, the measurements are comparable with those from well-calibrated wave buoys, and have an accuracy on order  $\pm 10\%$  (Webb, 1981). Because the wave skewness is proportional to wave steepness (Huang and Long, 1980) it may be possible to use the measured wave height and skewness to estimate wave length. However the skewness of typical ocean waves tends to be small, and the estimate of wavelength may not be reliable in practice.

The strength of the reflected pulse is a function of the structure of the surface and its dielectric constant. The latter determines the reflectivity, and the former influences the geometric distribution of the scattered signal and thus the energy reflected back towards the satellite. Over the oceans, the dielectric properties of the surface are nearly constant, and roughness dominates, particularly the roughness due to waves with greatest slope, waves having length comparable to the radar wavelength. These short waves are dominated by the local wind, thus the amplitude of the reflected pulse is proportional to the wind speed. Essentially, the radar behaves as a scatterometer, but differs from wind-measuring radars by looking straight down rather than at greater angles. This reduces the sensitivity and accuracy of the wind measurement, resulting in a typical accuracy of  $\pm 2$  m/s for speed. Note that only speed can be measured, the radar pulse contains no information about wind direction.

Over ice and snow, changes in both dielectric constant and roughness are important, and these allow the altimeter to measure the extent of pack ice, the concentration of multiyear ice in the Arctic, and grain size of snow on glaciers.

Rain in the atmosphere above the surface also reflects the altimeter pulse, the reflected power being a function of rain rate (figure C.1) and the proportion of the radar beam being filled by rain cells. By observing the reflected power at two heights, one near the surface, and one a few kilometers above the surface, it should be possible to measure both rain rate and rainfall area. By combining the radiometer signal, which measures emission from rain, with the radar signal, which measures scatter from rain, it should be possible to obtain a more precise estimate of rain rate (Ulbrich and Atlas,

Table C.1 - Auxiliary Measurements Available from TOPEX

Variable	Source of Data	Accuracy	
Wave height	Altimeter pulse shape	$\pm 10$	%
Wind speed	Altimeter pulse amplitude	$\pm 2$	m/s
Position of pack-ice edge	Altimeter pulse amplitude	$\pm 3$	km
Percentage ice cover	Dual-frequency radiometer	$\pm 15$	%
Percentage multiyear ice	Dual-frequency radiometer	—	
Rain rate	Radiometer plus altimeter	$\pm 30$	%
Ionospheric electron content	Dual-frequency altimeter	$\pm 4 \times 10^{16}$	e/m <sup>2</sup>
Integrated water vapor	Dual-frequency radiometer	$\pm 2$	m
Topography of ice and land	Altimeter pulse delay	$\pm 1$	m

1978). Essentially, emission, scatter, and rain rate are all different moments of the rain drop size distribution. The distribution is accurately specified on average by two parameters, and two separate moments, measured by emission and scatter, define a third, rain rate, with experimental accuracies on order  $\pm 10\%$ . However, practical difficulties in making measurements from space will produce somewhat less accurate estimates of rainrate.

A pair of altimeters simultaneously measuring the height of a satellite using two widely separated frequencies can measure both the height of the satellite and the integrated electron content of the ionosphere (section 4.1.7). Plasmas are dispersive media for the propagation of radio waves, while atmospheric moisture, which also delays radio signals, is nondispersive. Thus the pulse delay at two frequencies depends uniquely on electron content in the ionosphere.

Water vapor in the troposphere, measured by radiometers that observe radiation at frequencies close to the water-vapor absorption band at 22 GHz, is yet another useful variable. However, other processes, particularly foam on the ocean surface, also radiate in this band; and radiation in at least one other band must be observed at the same time. This done, a dual-frequency radiometer can measure both water vapor (and rain when it is present), and one other variable, usually a combination of wind speed and cloud liquid-water content. Over relatively cloud-free ocean, the influence of wind speed should dominate, allowing this variable to be measured. Over ice and snow, the variable dielectric properties and roughness of the surface dominate, allowing the radiometer to observe ice type and extent, and the percentage of sea covered by ice (Gloersen *et al*, 1978), observations that complement to some extent the altimeter observations.

These various auxiliary measurements, together with a rough estimate of their expected accuracy, are summarized in table C.1.

## C.2 Coastal Oceanography

In contrast to the deep ocean, the coastal oceans tend to be dominated much more by the influence of the bottom, nearby coasts, and continental air masses. Coastal regions tend to be used much more extensively for commerce, fisheries, mining,

and recreation. Finally, people tend to live in coastal areas and to build at the water's edge structures that are placed in peril during storms. Particularly for these latter reasons, the coastal areas have great economic importance and this leads to a correspondingly great interest in the dynamics of coastal currents, waves, and erosion, especially during storms.

To some extent studies of these regions require extensive measurements made over small areas, measurements best made by instruments on aircraft or at the surface. To some extent, the studies require measurements made over much larger areas, measurements that could be made by satellites. And to some extent, the work requires observations that can only be made from satellites. In particular, accurate measurements of the topography of the sea surface, coupled with information about winds and waves, are essential for elucidating the dynamics of coastal seas during storms. Of lesser but still significant importance is a knowledge of local tides and tidal currents, particularly in shallow seas that are potential sites for offshore structures.

When storm winds blow shoreward over relatively shallow water, they produce substantial rises in sea level, piling up water against the shore and producing flooding, erosion, and damage to coastal structures. During severe storms such as typhoons and hurricanes the storm surge can be three to seven meters high, can inundate large areas of land, and can lead to great loss of life and damage to property. Areas such as the Gulf of Mexico, the southern end of the North Sea, and the Bay of Bengal are notorious. In these places the worst storms have killed hundreds to thousands of people, destroyed cities, and ruined tens of thousands of acres of farmland. Galveston in 1903, Holland in 1953, and Bangladesh in 1970 immediately come to mind.

The severity of damage is related to the height of the storm surge, and this in turn is determined by poorly understood but complex interactions among wind speed, the size of breaking waves, the phase of the tide, bathymetry, and wind-and-wave generated currents. Breaking waves carry momentum toward the coast, scour the bottom, and stir up sediments. These are transported elsewhere by currents to produce new shoals and bars which further influence currents and waves.

Despite the combined danger of wind and waves, waves by themselves cannot be ignored, and they cause problems even when generated by distant storms. The continual erosion of the Southern California coast by waves from North Pacific winter storms is a noteworthy example. Incoming waves are influenced by offshore shoals, and can be focused to produce locally large breakers along some beaches. These breaking waves in turn produce currents which redistribute sand on beaches, causing local erosion or the deposition of new beaches or offshore bars. The latter are particularly important when they occur along sea lanes or at the entrance to harbors.

The tide is the third important process in coastal regions. It changes sea level and influences navigation over shoals, it produces strong currents which redistribute sediments, and it can ameliorate or accentuate the influence of storm surges and breaking waves. On a global scale, the dissipation of tides in shallow seas slows the rotations of Earth and the moon about the Earth.

Further progress in understanding the nature of surges, the focusing of waves, the dissipation of tides, and the dynamics of coastal currents requires measurements of winds, waves, and sea level, in regions where the bathymetry is well known, during times of strong winds, and especially during storms. In principle, all but the bathymetry can be measured from space, but such measurements have not been made solely because surges, being rare, have not yet coincided with satellite observations. Nevertheless, the importance of the studies, as well as their potential value, leads to continuing attempts to study the influence of storms on these regions. The possibility of very useful observations being made by TOPEX (or Noss) cannot be ignored.

### C.3 Polar Studies

The intimate connection between ice and climate is well known and long studied, for who has not read of the ice ages and their influence on the recent geologic past, or of the little ice age and its influence on recent history. Yet the relationship, although clear, is not yet understood; and it continues to excite the interest of glaciologists, polar scientists, oceanographers, and climatologists. All seek more detailed information about the thickness, stability and extent of the Antarctic ice sheet, the thickness of the Greenland ice sheet, and the extent and solidity of the Arctic ice cover. Such information, while important and necessary, is difficult to obtain, particularly in winter when ice sheets reach their maximum extent. Fortunately satellite measurements are not only useful, but often are more accurate and extensive than conventional surface observations. The nature of the polar problems and the ability of satellites to contribute their solution have been elegantly explored in "ICEX, The Ice and Climate Experiment" (NASA, 1979). In the next few paragraphs, we can do no more than paraphrase a few of the more pertinent ideas.

Continental ice sheets are a summation of Earth's climate over the past few hundred to a few thousand years, and perhaps are sensitive indicators of climate. Those who study these great glaciers seek to know whether the sheet is growing or contracting, the speed with which the ice flows to the sea, and whether or not the flow is likely to surge, leading to a rapid decrease in the size of the sheet and a concomitant rise in sea level. The primary measurement for these studies is the thickness of the ice sheet relative to the geoid with an accuracy of a few centimeters repeated from decade to decade. Such measurements would not only directly detect changes in the thickness of the glacier, but would also provide a profile of the glacier from which it would be possible to calculate the internal flow of the ice. Although TOPEX will not observe Greenland or Antarctica if it is in a 65° orbit, it will provide an accurate means of tying together the north-south arcs of other altimetric satellites (such as Noss), enabling these satellite to make far more accurate profiles of the polar regions than would be possible without TOPEX.

Over shorter time scales, the seasonal advance and retreat of the sea ice edge is also important. Ice strongly inhibits the exchange of heat and water vapor between polar seas and the atmosphere, thus controlling the amount of water available to form snow in northern latitudes; it changes the albedo of Earth, thus influencing the global heat budget, and it interferes with commerce at high latitudes. Again, TOPEX will be useful mainly for supplementing the winter observations of Noss, however these additional observations may be particularly useful for tracking the rapid advance of the ice front in regions and times when the front is rapidly advancing or retreating.

### C.4 Other Studies

Of the remaining auxiliary measurements that could be made by TOPEX, perhaps the most useful would be the ability to measure rain rate. Observations of oceanic rain are seldom made by conventional methods because they are so inaccurate, and both rain rates and cumulative rainfall are very poorly known in most oceanic regions and almost unknown in others. Yet the observations are important for studies of climate and air-sea interaction, for predicting the propagation of radar and communication signals, and for understanding the general circulation of the atmosphere and the dynamics of storms. Observations from TOPEX will be unique, for the satellite will make coincident observations of radio-frequency scatter and emissions, observations that should provide accurate estimates of rain. In addition, TOPEX will sample the atmosphere at various times of the day rather than at the fixed times of the meteorological satellites, and will provide additional observations of fast-moving storms such as hurricanes that would certainly be missed by a single satellite system.



More speculative would be the use of the altimeter to observe slow changes in land elevations. Many relatively flat areas are slowly changing elevation due to pumping of ground water or oil, and because of tectonic forces. Yet observations with accuracies of tens of centimeters are difficult by conventional means. The controversy surrounding the existence of the Palmdale bulge is a simple but not isolated example. Clearly, TOPEX should be capable of measuring the elevation of plains, such as the flat desert near Palmdale, and to repeat the measurements from year to year. Yet such measurements have not been made, except for a few preliminary observations from Seasat, so it will be useful to attempt such measurements and an assessment of their accuracy and repeatability.

Lastly, the measurements of electron content of the ionosphere will provide insights into the dynamics of this region. Observations in the past have been primarily along lines as a function of time, while the satellite will make repeated observations as a function of position. The high spatial resolution of the measurements will reveal the structure of ionospheric "bubbles," will provide global maps of ionospheric activity, and will show the spatial response of the ionosphere to external forcing.